Preliminary Assessment of Impact of Tsunami in Selected Coastal Areas of India

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CONTENTS

1. Background

Tsunamis are among the most terrifying natural hazards known to man and have been responsible for tremendous loss of life and property throughout history. Because of their destructiveness, tsunamis have notable impact on the human, social and economic sectors of our societies. In the Pacific Ocean, where the majority of these waves have been generated, the historical record shows wide scale destruction. In Japan, which has one of the most populated coastal regions in the world and a long history of earthquake activity, tsunami has destroyed large coastal populations. There is also a history of tsunami destruction in Alaska, in the Hawaiian Islands in South America, Japan and elsewhere in the Pacific.

Destructive tsunamis have also occurred in the Indian Ocean and in the Mediterranean Sea. The most notable tsunami in the region of the Indian Ocean was that associated with the violent explosion of the volcanic island of Krakatoa in August 1883. A 30 m (100 feet) tsunami resulting from this explosion killed 36,500 people in Java and Sumatra. The violent eruption and explosion of the volcano of Santorin, in the fifteenth Century B.C. generated a giant tsunami which destroyed most of the coastal Minoan settlements on the Aegean Sea islands acting as the catalyst for the decline of the advanced Minoan civilization.

Tsunamis that can travel across an ocean and attack a coastal area far away from the source of generation are called distant Tsunamis or Teletsunamis, while tsunamis that are confined in an area near the source are called local Tsunamis.

2 The Physics of Tsunamis - the mechanisms of generation and propagation

2.1 What is a Tsunami?

A Tsunami is a wave train, or series of waves, generated in a body of water by an impulsive disturbance that vertically displaces the water column. Earthquakes, landslides, volcanic eruptions, explosions, and even the impact of cosmic bodies, such as meteorites, detonation of nuclear devices near the sea can give rise to such

destructive sea waves so called Tsunamis. By far the most destructive tsunamis are generated from large shallow-focus earthquakes with an epicenter or fault line near or in the ocean. Vertical displacements of the earth's crust along the rupture resulting from such earthquakes can generate destructive tsunami waves which can travel across an ocean spreading destruction across their path. Although the sources for formation of tsunami are considered as point sources, the tsunami waves generated can be very destructive locally, the energy of the waves is rapidly dissipated as they travel across the ocean, can ravage coastlines, causing property damage and loss of life. The speed of the tsunami is governed by the water depth. Speed reduces and wave height increases as it approaches the shore.

2.2 What does "Tsunami" mean?

Tsunami is a Japanese word with the English translation, "harbour wave". Represented by two characters, the top character, "tsu" means harbour, while the bottom character, "nami" means "wave." In the past, tsunamis were sometimes referred to as "tidal waves" by the general public, and as "seismic sea waves" by the scientific community. The term "tidal wave" is a misnomer; although a tsunami's impact upon a coastline is dependent upon the tidal level at the time a tsunami strikes, tsunamis are unrelated to the tides. Tides result from the imbalanced, extraterrestrial, gravitational influences of the moon, sun, and planets. The term "seismic sea wave" is also misleading. "Seismic" implies an earthquake-related generation mechanism, but a tsunami can also be caused by a nonseismic event, such as a landslide or meteorite impact.

2.3 Influence of earthquakes in generating Tsunamis

If man has a way of demarcating and classifying the various regions of earth into several countries and continents, nature has its own way too. The earth's surface is not one continuous piece of landmass. On the other hand, it is broken up into several large and small plates. A plate (also called lithospheric plate) is a massive, irregularly shaped slab of solid rock, generally composed of both continental and oceanic lithosphere. These plates, each about 50 miles thick, are not anchored to a particular place; they move relative to one another at an average speed of a few

inches a year. And earthquakes and volcanic eruptions occur when these plates collide at their boundaries.

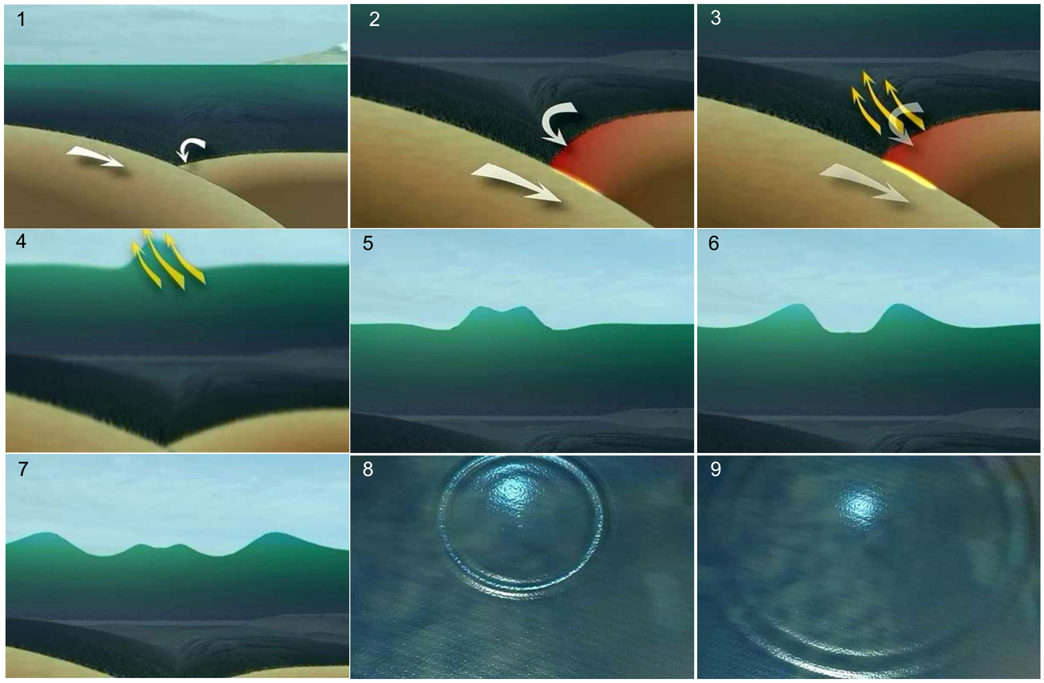
But not all plate movements lead to collision. Three types of movement are recognized at the boundaries between plates: convergent, divergent and transform. At the divergent boundaries new crust is formed when lava flows out pushing the plates away from each other; convergent boundaries, on the other hand, lead to plate destruction as one plate dives (subducts) under another. Crust is neither created nor destroyed at the transform boundaries as the plates just slide past each other horizontally. The formation of new crust, called sea floor, spreading at the divergent boundaries and destruction at convergent plate boundaries happen at the same rate globally. And this is the essence of plate tectonics, which goes to explain how volcanic eruptions, and earthquakes that ravage the earth's surface happen.

Tsunamis can be generated when the sea floor abruptly deforms and vertically displaces the overlying water. Tectonic earthquakes are a particular kind of earthquake that are associated with the earth's crustal deformation; when these earthquakes occur beneath the sea, the water above the deformed area is displaced from its equilibrium position (Fig.1). Waves are formed as the displaced water mass, which acts under the influence of gravity, attempts to regain its equilibrium and the size of the resultant tsunami waves is determined by the quantum of the deformation of the sea floor. More the vertical displacement, greater will be the size of the waves. As a rule, all earthquakes do not produce tsunamis. When large areas of the sea floor elevate or subside, a tsunami can be created.

Large vertical movements of the earth's crust can occur at plate boundaries. Plates interact along these boundaries called faults. Around the margins of the Pacific Ocean, for example, denser oceanic plates slip under continental plates in a process known as subduction. Subduction earthquakes are particularly effective in generating tsunamis. The earthquake's magnitude, depth, fault characteristics and coincident slumping of sediments or secondary faulting also determine the size of the tsunamis.

If plate interactions on land cause earthquakes, those that occur in the sea pose the biggest risk of generating tsunamis. Earthquakes occurring on land do not cause

death directly; buildings that collapse do. Similarly, earthquakes that occur in the sea do not kill life; tsunamis that are produced by them do.



(Courtesy: Prof. Miho Aoki, University of Alaska)

FIG 1. Visualisation of Tsunami generation by a subduction zone earthquake

2.4 Influence of landslides, volcanic eruptions and cosmic collisions in generating Tsunamis

A tsunami can be generated by any disturbance that displaces a large water mass from its equilibrium position. In the case of earthquake-generated tsunamis, the water column is disturbed by the uplift or subsidence of the sea floor. Submarine landslides, which often accompany large earthquakes, as well as collapses of volcanic edifices, can also disturb the overlying water column as sediment and rock slump downslope and are redistributed across the sea floor. Similarly, a violent submarine volcanic eruption can create an impulsive force that uplifts the water column and generates a tsunami. Conversely, supermarine landslides and cosmic-body impacts disturb the water from above, as momentum from falling debris is transferred to the water into which the debris falls. Generally speaking, tsunamis generated from these mechanisms, dissipate quickly and rarely affect coastlines distant from the source area.

2.5 Difference between Tsunami waves and other water waves

Wind flowing across a lake or ocean can create wrinkles on the water surface and produce short waves restricted to shallow layer. Tides (high and low) that sweep the globe every day also produce waves. Means by which tsunamis generated have been explained in the previous sections.

Tsunamis are unlike wind-generated waves, which are observed on a local lake or at a coastal beach, in that they are characterized as shallow-water waves, with long periods and wave lengths. The wind-generated waves are rhythmically rolling in, one wave after another, might have a period (time between two successive waves) of about 10-20 seconds and a wave length (distance between two successive waves) of 100-200 m. A tsunami, on the other hand, can have a wavelength in excess of 500 km and period of ten minutes to two hours (Fig.2). It is because of their long wavelengths that tsunamis behave as shallow-water waves. Tsunamis are often taller than normal wind waves, but they are much more dangerous.

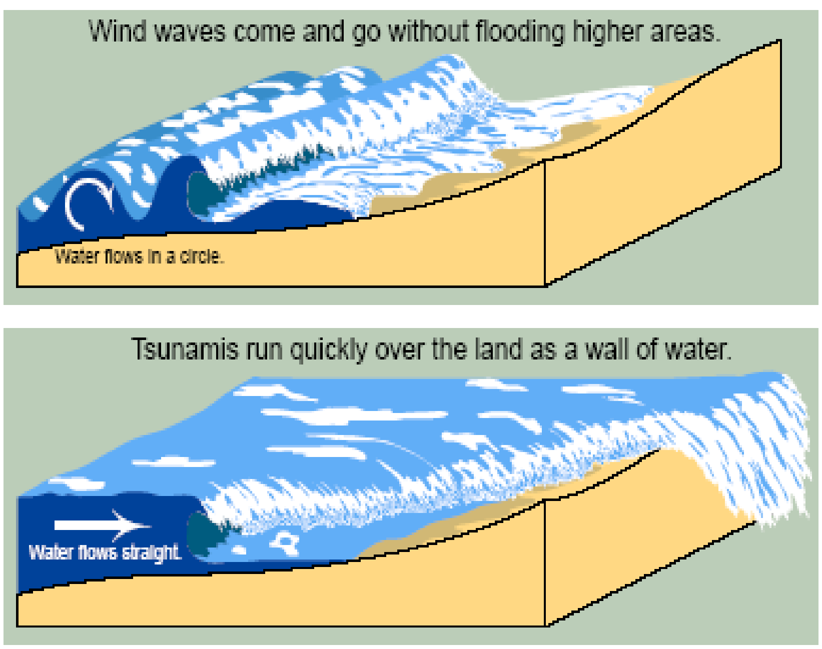


FIG 2. Difference between Wind waves and Tsunami waves
(Courtesy: www.ess.washington.edu/tsunami/index.htm)

2.6 Tsunamis travel to long distance

As a result of their long wave lengths, tsunamis behave as shallow-water waves. A wave becomes a shallow-water wave when the ratio between the water depth and its wave length gets very small and the rate at which a wave loses its energy is inversely related to its wavelength. Since tsunamis have a very large wavelength, in excess of 500 km, it will lose little energy as it propagates. Shallow-water waves move at a speed that is equal to the square root of the product of the acceleration of gravity (9.8 m/s) and the water depth. Hence in very deep water, a tsunami will travel at high speeds and travel great distances with limited energy loss. For example, when the ocean is more than 5000 m deep, unnoticed tsunami travel about 890 km/hr, the speed of a jet airplane and at 1000 m water depth it would travel at 356 km/hr. So a tsunami travels at different speeds in the ocean; slow in shallow water and fast in deep water. Because the rate at which a wave loses its energy is inversely related to its wave length, tsunamis not only propagate at high speeds, they can also travel great, transoceanic distances with limited energy losses.

But what in the first place provides the force needed to allow a tsunami to travel a long distance? Tsunamis are what are called long gravity waves. There are two interacting processes that allow these waves to propagate. The first is the slope of the sea surface, which creates a horizontal pressure force. The second is the piling up (or lowering of sea surface) as water moves with different speeds in the direction that the wave form is moving. When these two processes have the right relationship in time, they create propagating waves.

As the tsunami crosses the deep ocean, its wavelength (distance from crest to crest) may be hundred kilometres or more and its amplitude (height from crest to trough) will be in the order of a few feet or less. They cannot be felt aboard ships nor can they be seen from the air in the open ocean. However, radar satellites can detect these changes.

2.7 What happens to a Tsunami as it approaches land?

As a tsunami leaves the deep water of the open ocean and travels into the shallower water near the coast, it transforms and travels at a speed that is related to the water

depth - hence, as the water depth decreases, the tsunami slows. The tsunami's energy flux, which is dependent on both its wave speed and wave height, remains nearly constant. They race onto shallow water regions, pass into continental coasts and their speed diminishes which results in increase in the wave height in order to conserve the total energy. This results in decreasing the distance between individual waves in a process called 'shoaling'. The conservation of energy requires that the amplitudes (height) of the waves grow larger as the waves slow down. The height of the wave rises up to 30 feet or more and the total energy of the tsunami remains a constant. Because of this shoaling effect, a tsunami, imperceptible at sea, may grow to be several meters or more in height near the coast. When it finally reaches the coast, a tsunami may appear as a rapidly rising or falling tide, a series of breaking waves, or even a bore (Fig.3).

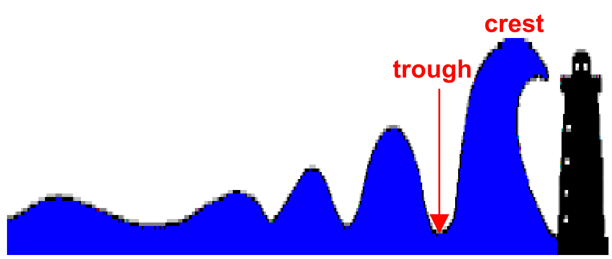


FIG 3. Movement of Tsunami waves as it reaches towards coast

2.8 What happens when a Tsunami encounters land?

As a tsunami approaches shore it begins to slow and grow in height. Just like other water waves, tsunamis begin to lose energy as they rush onshore - part of the wave energy is reflected offshore, while the shoreward-propagating wave energy is dissipated through bottom friction and turbulence. Despite these losses, tsunamis still reach the coast with tremendous amounts of energy. Tsunamis have great erosional potential, stripping beach sand, undermining trees and other coastal vegetation. Capable of inundating, or flooding, hundreds of meters inland past the typical high-water level, the fast-moving water associated with the inundating tsunami can crush homes and other coastal structures. Tsunamis may reach a maximum vertical height onshore above sea level, often called a 'run-up height', of 10, 20 and even 30 meters especially near the coast (Fig.4).

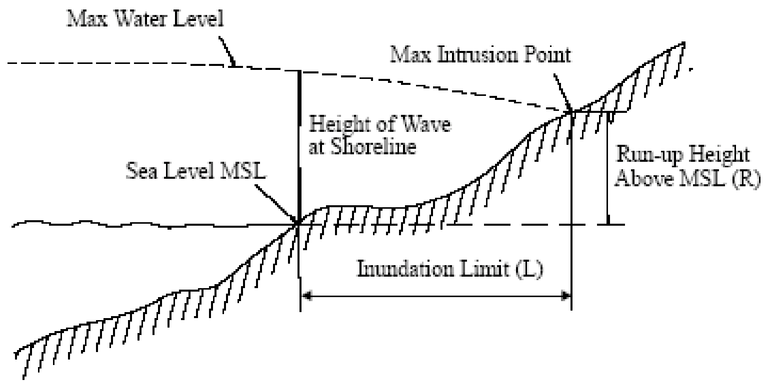


FIG 4. Schematic diagram showing measurement of Run-up height.

(Courtesy: Gica & Teng, 2003)

Run-up is usually expressed in meters above normal tide or Mean Sea Level. Run-ups from the same tsunami can be variable because of the influence of the geomorphology (shape) of the coastline. In one coastal area destructive waves can be large and violent with large damaging activity, while in another area without being violent cause extensive flooding with rise in water level to a few meters. The inundation of the area can be up to 2 to 5 km inland especially at locations where estuaries that have good depth profile. While retreating, the waves with considerable velocity tend to carry loose objects and people out to sea. The extent of damage depends on extent of run up height, velocity of the water, local topography and land utility pattern (say settlement, agriculture, forestry etc). The loss of human life in a single tsunami could be as much as 1,00,000 and damage to properties to several millions of dollars.

2.9 Receding of ocean as a signal of Tsunami at coast

The arrival of tsunami wave to the coast can be different. The crest of the wave isn't the first to arrive - the trough is. This is often the case when the tsunami originates from an oceanic earthquake associated with land subsidence or sinking, which causes the water column to drop down at the earthquake site. In this case, instead of extremely high water levels, the first sign of a tsunami is what appears to be an unusually low-tide (Fig.5). Although onlookers might be intrigued by this unusual

site, this major withdrawal of the sea should be taken as a warning that a tsunami wave will soon follow.

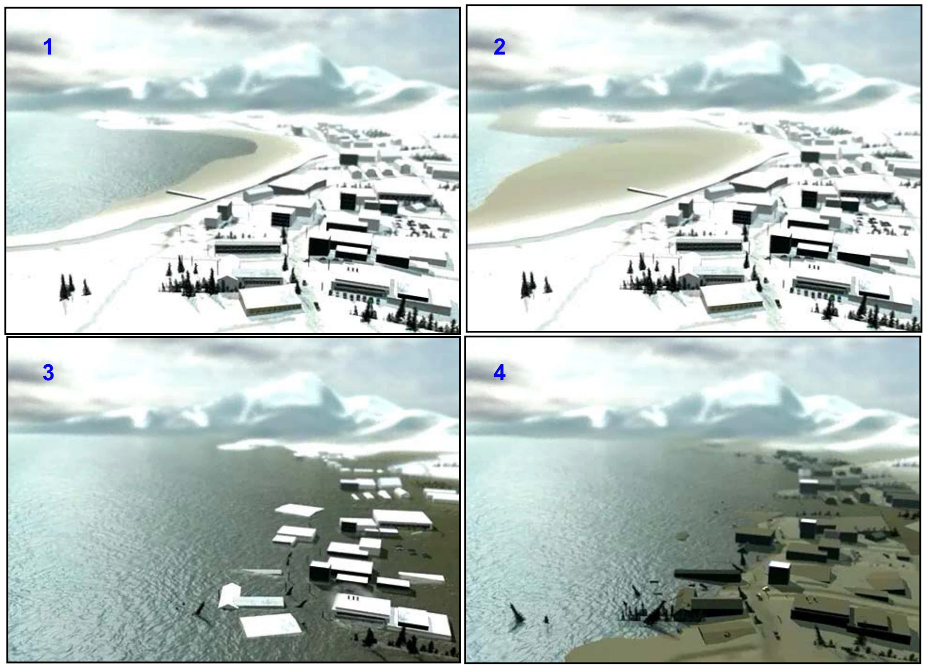


FIG 5. Computer animated visuals of Tsunami seen at the coast
Receding of sea is seen first followed by inundation of coastal area.
(courtesy: Prof. Moho Aoki, University of Alaska)

As the coastal ocean waters recede from the shore, it often leaves large portions of the sea floor exposed. Individuals who do not recognize this as a common precursor to tsunami waves often find themselves gravitating toward the exposed shore. Experts believe that a receding ocean may give individuals more familiar with "nature's tsunami warning signal" as much as a five-minute warning to evacuate the area. This cycle may be repeated several times as successive wave crests arrive five minutes to an hour apart.

2.10 Understanding Tsunami Source Mechanism and Potential Terminal Runup

To forecast tsunamis and determine terminal runup and destructiveness, one must be able to evaluate the parameters of the tsunami source mechanism in real time, often from inadequate data. Tsunami source mechanism analysis is difficult given the time constraints of a warning situation. Despite the great speed, tsunami waves travel much slower than the seismic waves. Hence earthquake information is often

available hours before the tsunamis are able to travel across the ocean. It will suffice to say that forecasting the runup and potential destructiveness of a tsunami at a distant shore will depend greatly on determining the seismic parameters of the source location such as magnitude of the earthquake, its depth, its orientation, the length of the fault line, the size of the crustal displacements, and depth of the water. Refraction and diffraction processes will affect the energy and height of the tsunami waves as they travel across the ocean. These effects must also be determined. Finally, terminal height, run-up, and inundation of the tsunami at a point of impact will depend upon the energy focusing effect, the travel path of the waves, the coastal configuration, and the offshore bathymetry, only to name a few.

Tsunami run-up is the vertical distance between the maximum height reached by the water on shore and the mean-sea-level surface. Contrary to meteorological predictions, tsunami run-up is not possible to forecast with a great degree of accuracy. The reason for this inadequacy is that the Tsunami Warning System works in a real time frame of short duration, often with inadequate data and information. Problems of communications and lack of sufficient station density, often complicate the process. Forecasting tsunamis requires adequate understanding of the phenomenon, good and expeditious collection of earthquake and sea level data, and accurate and expeditious assessment and interpretation of this data.

3 History of Tsunamis in the world and extent of inundation

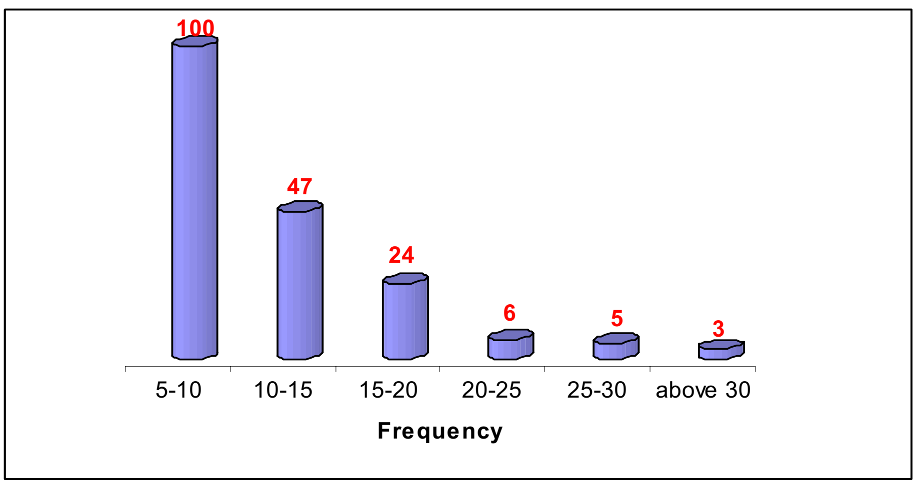
Tsunamis are generated when the epicenter of an earthquake having a magnitude of more than Ms 7.0 located on seabed. In the Pacific Ocean where the tsunamis occur mostly, 79 tsunamis were observed with 117 casualties but with extensive damages to properties. According to the Tsunami Laboratory in Novosibirsk during the 101-year period from 1900 to 2001, 796 tsunamis were observed or recorded. 117 caused casualties and damage most near the source only. At least nine caused widespread destruction throughout the Pacific. The greatest number of tsunamis during any one year was 19 in 1938, but all were minor and caused no damage. There was no single year of the period that was free of tsunamis. Details of Run up levels occurred during last one decade in the Pacific is given in Table 1.

TABLE 1. Run up levels recorded during Tsunamis occurred between 1992 and 2001 in the Pacific Ocean

Date	Location	Magnitude of earthquake at source (M)	Max Run-up (m)	Killed (nos.)
09.02.92	Nicaragua	7.2	10	170
12.12.92	Flores Island	7.5	26	1000
07.12.93	Hokkaido	7.6	30	200
06.02.94	Java	7.2	14	220
10.04.94	Kuril Island	8.1	11	11
11.14.94	Nubdiri	7.1	7	70
02.21.96	Peru	7.5	5	12
07.17.98	New Guinea	7.0	15	2000
06.23.01	Peru	8.3	5	50

Source: Pacific Tsunami Warning Centre (http:www.prh.noaa.gov/ptwc/aboutTsunamis.htm)

In the Pacific region, 17% of the total tsunamis were generated in or near Japan. The distribution of tsunami generation in other areas is as follows: 15% in South America, 13% in New Guinea Solomon Islands, 11% in Indonesia, 10% in Kuril Islands and Kamchatka, 10% in Mexico and Central America, 9% in Philippines, 7% in New Zealand and Tonga, 7% in Alaska and West Coasts of Canada and the United States, and 3% in Hawai.



(Source: National Geophysical Data Centre, NOAA)

FIG 6. Frequency distribution map showing Tsunami Runup heights (m) from all over the world during 1940-2004

The history of tsunamis generated all over the world since 1940 revealed that the tsunami runup height of 5-10 m was recorded for maximum number of times and the intensity of tsunami occurrences decreased with increasing runup heights (Fig.6). Run-up heights between 20 and 30 m occurred for 11 times while that exceeding 30 m recorded only thrice.

3.1 History of Tsunamis affecting Indian Ocean

Although not as frequent as in the Pacific Ocean, tsunamis generated in the Indian Ocean pose a great threat to all the countries of the region. The most vulnerable are: Indonesia, Thailand, India, Sri Lanka, Pakistan, Iran, Malaysia, Myanmar, Maldives, Somalia, Bangladesh, Kenya, Madagascar, Mauritius, Oman, Reunion Island (France), Seychelles, South Africa and Australia.

Tsunamis occur seldom in the Indian Ocean region, and in the last 300 years, this region recorded 13 tsunamis (Table 2) and 3 of them occurred in Andaman and Nicobar region for which the details of location of epicentre, death/damage caused etc. are not known, data on run-up heights indicate to the extent of 4 m in Port Blair with Nicobar recording very low (0.76 m). Among these, the 1945 tsunami had a maximum run up of 13 m in Pakistan and resulted in death of 4000 people following an earthquake of magnitude 8.2 Ms in the Arabian Sea. Overall, the run-up levels varied from 1 to 13 m. In 1977, one of the strongest earthquake of magnitude Ms 8.1 struck west of Sumba Island in Indonesia, but there were no reports of casualties in India due to this tsunami. Apart from those listed in Table 2, there may be additional destructive tsunamis in the Indian Ocean that have not been properly documented. For example villagers of Simeulue Island, off the coast of Sumatra, speak of a destructive tsunami in 1907 that had killed thousands of people.

TABLE 2. Run-up level for Tsunami occurred between 1700 and 2004 in the Indian Ocean

S. No	Name of affected location	Run up heights (m)	Year/ Date	Earthquake Magnitude at source	Source location
1.	Tributaries of the Ganges river (Bangladesh)	1.83	12.04.1762	NA	Bay of Bengal
2.	--	--	1847	--	Great Nicobar Island
3.	Port Blair, Andaman Islands	4.00	19.08.1868	MW 7.5	Bay of Bengal
4.	Car Nicobar Island, Nicobar Islands	0.76	31.12.1881	MS 7.9	Car Nicobar Islands, Andaman Sea
5.	Dublat, India	0.30			
6.	Nagapattinam, India	1.22			
7.	Port Blair, Andaman Islands	1.22			
8.	Chennai	1.5 (wave height)	26.08.1883	Krakatao volcanic eruption	Islands of Java and Sumatra
9.	Andaman & Nicobar Islands	NA	26.6.1941	MW 7.7	Andaman Sea (12.5°N; 92.57°E)
10.	Mumbai, India	1.98	27.11.1945	MS 8.3	Arabian Sea (24.5°N; 63°E)
11.	Karachi, Pakistan	1.37			
12.	Ormara, Pakistan	13.00			
13.	Pasni, Pakistan	13.00			
14.	Victoria, Mahe Island, Seychelles	0.30			
15.	Not felt in India	--	19.08.1977	MS 8.1	West of Sumba Island, Indonesia (11.09°S; 118.46°W)
	Cocos Islands, Australia	0.30	18.06.2000	MS 7.8 MW 7.9	Arabian Sea

Source: National Geophysical Data Centre, NOAA, USA
(www.ngdc.noaa.gov/nmdc/servlet/ShowDatasets)

4 Seismotectonics of the Indian Ocean region and potential Tsunami generating sources

Harsh Gupta (2005) stated that globally there are three major belts which account for almost 95% of earthquake activity. According to him, the belt along which most of the earthquakes occur is called the Circum-Pacific belt which goes around the rim of the Pacific Ocean. The second most active belt is the Alpide-Himalaya seismic belt which starts from southeast Asia near Java-Sumatra, continues through Andaman Nicobar Islands, India-Burma border region, swings through north of India in the foothills of Himalayas and then moves west through Iran into Greece and Italy. The third major seismic belt consists of mid-oceanic ridges which account for small magnitude earthquakes. These can be seen in Pacific, Atlantic and Indian Oceans. Majority of earthquakes occur at shallow depths (0-70 km) whereas some occur at intermediate depths (70-300 km) and a few at deeper depths (300-700 km).

Although not as destructive as the 26 December 2004 event was, many more tsunamis have been generated by large earthquakes in subduction zones bordering the Indian Ocean and by smaller magnitude events along the Central Indian and Carlsberg mid-oceanic ridges. Among the major tsunamis listed in Table 2, the Krakatao volcanic eruption generated the deadliest tsunami in 1883 which killed 37,000 people in the islands of Java and Sumatra.

Scientists at Columbia University's Lamont-Doherty Earth Observatory (LDEO) report direct evidence that one of the Earth's great crustal plates is cracking in two. Orman et al. (1995), have confirmed that the Indo-Australian Plate, long identified as a single plate on which both India and Australia lie, appears to have broken apart just south of the Equator beneath the Indian Ocean. The break has been underway for the past several million years, and now the two continents are moving independently of one another in slightly different directions. According to USGS, the India tectonic plate has been drifting and moving in a north/northeast direction for some 50 million years, colliding with Eurasian tectonic plate and forcefully raising the Tibetan Plateau and the Himalayan Mountains (Fig.7). As a result of such migration and collision with both the Australian and the Eurasian tectonic plates and subplates, the Indian plate's eastern boundary is a diffuse zone of seismicity and deformation,

characterized by extensive faulting and earthquakes that can generate moderate to destructive tsunamis.

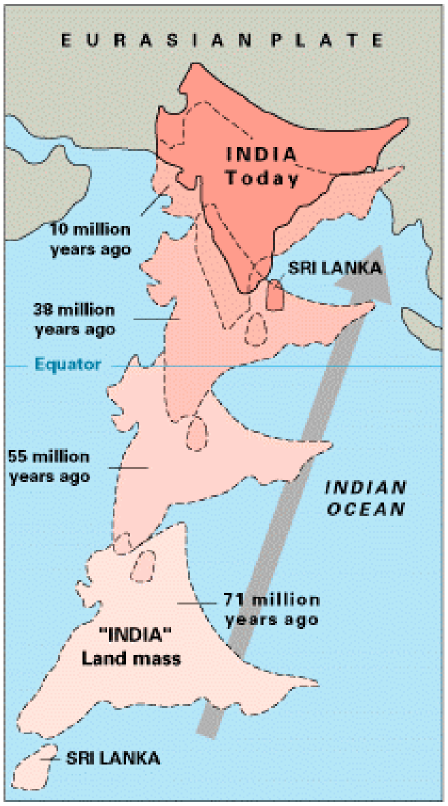
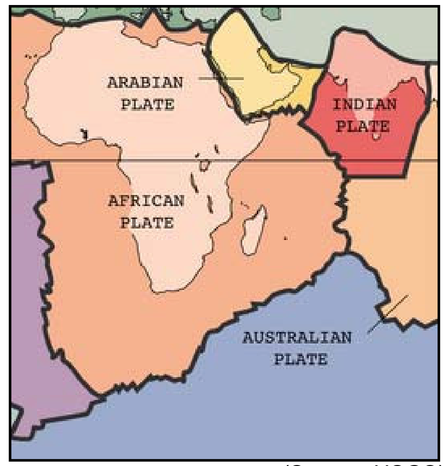


FIG 7. Migration of Indian Tectonic Plate (Source: USGS)



(Source: USGS)

FIG 8. Tectonic plates of Indian Ocean.

In the western part of Indian Ocean, the interaction of the India plate with the Arabian and Iranian microplates of the Eurasian block has created an active subduction zone along the Makran coast of Pakistan (Fig.8). A major fault in this region has produced tsunamigenic earthquakes recently and in the distant geologic past. This major fault is of the same character as the West Coast fault along the coast of Maharashtra, India - which is also a region that can produce tsunamigenic earthquakes. Further south on the western side the Indian tectonic plate is bounded by the Central Indian and Carlsberg mid-ocean ridges, a region of shallow seismicity. To the east, subduction of the Indo-Australian Plates beneath the Burma and Sunda Plates has formed the extensive Sunda Trench - a very active seismic region where large earthquakes are frequent. The volcanoes of Krakatau, Tambora and Toba, well known for their violent eruptions, are byproducts of such tectonic interactions. A divergent boundary separates the Burma plate from the Sunda plate in the north. The Burma plate encompasses the northwest portion of the island of Sumatra as well as

the Andaman and the Nicobar Islands, which separate the Andaman Sea from the Indian Ocean.

Destructive tsunamis can originate from earthquakes that occur along these principal tectonic sources. The major tectonic feature in the region is the Sunda Arc that extends approximately 5,600 km between the Andaman Islands in the northwest and the Banda Arc in the east. The Sunda Arc consists of three primary segments; the Sumatra segment, the Sunda Strait Segment and the Java Segment. These locations represent the area of greatest seismic exposure, with earthquake magnitudes of 8 or even more on the Richter scale - as the 26 December 2004 proved. Active tectonic interaction of this great arc has produced destructive earthquakes and tsunamis in the distant past and as recently as 1977, 1992 and 1994.

4.1 Earthquake of 26th December 2004:

On 26th December 2004, the Indian coastline experienced the most devastating tsunami in recorded history. The tsunami was triggered by an earthquake of magnitude Mw 9.3 at 3.316°N, 95.854°E off the coast of Sumatra (Fig.9) in the Indonesian Archipelago at 06:29 hrs making it the most powerful in the world in the

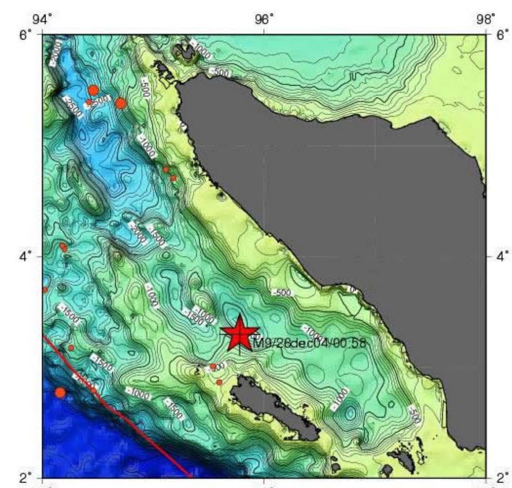
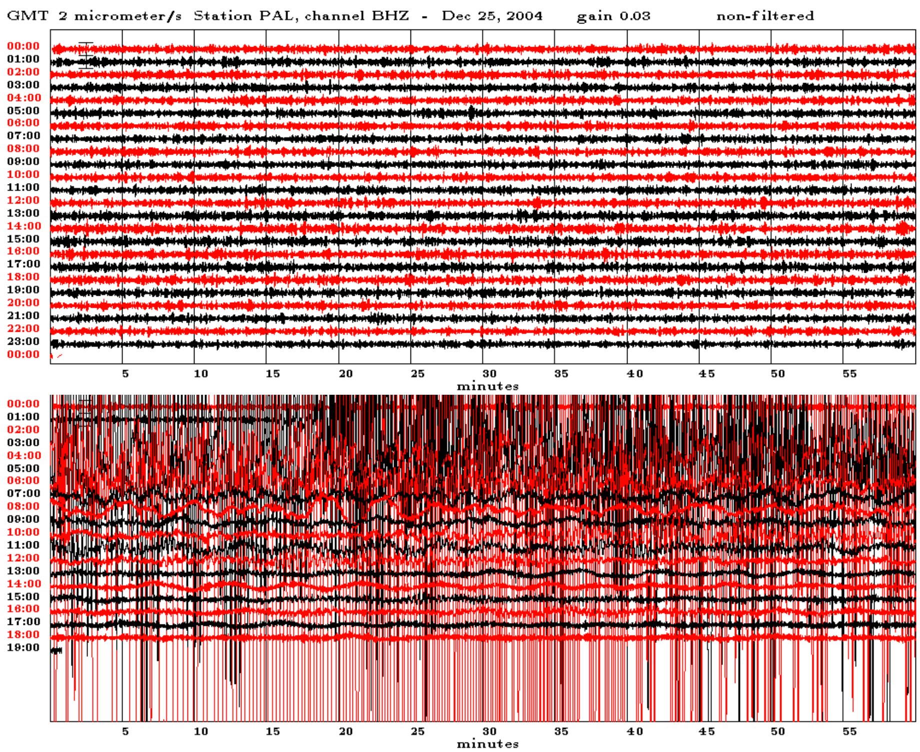


FIG 9. The topography at the site of the main seismic event (MW 9.3) generated using world digital topo data. According to this, the location of the event is about 1300 m deep from surface of the water (Source: USGS).

last 40 years. In confirmation to this, the recorded seismographs of LDEO show that at around 01:20 GMT on December 26, 2004 there was extraordinary oscillations that subsided 12 hours later. The seismograph for the previous day has shown regular activity (Fig. 10) but goes off the chart around 01:20 GMT and then subsides by 06:45 GMT. However, things did not become normal until 15:00 GMT.



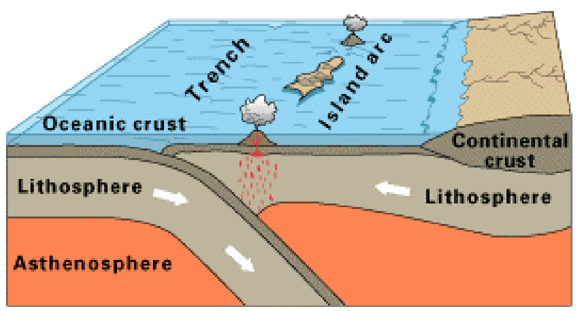
(Source: Lamont-Doherty Earth Observatory, Columbia University)

FIG 10. Seismographs for the periods 25th and 26th December 2004

The earthquake of 26th December 2004 occurred off northwest of Sumatra is not an unusual earthquake from the Plate Tectonics point of view. It has occurred in the vicinity of seismically active zone, close to Sunda Trench in the water depths of about 1300 m. The earthquake epicenter is located relatively at shallow depth, about 10 km below the ocean floor. The high magnitude, Mw 9.3 of the earthquake and its shallow epicenter have triggered tsunami in the northeast Indian Ocean. These were travelled in open ocean of the Bay of Bengal and subsequently transformed into a train of catastrophic oscillations on the sea surface close to coastal zones of Sri Lanka, east and west coasts of India.

4.1.1 Diving Indian plate

The earthquake of December 26 that occurred off the west coast of northern Sumatra took place at the interface between the Indian and Burma plates, where Burma plate has been referred by Andaman/Nicobar ridge that acts as a small tectonic plate (Curray *et al.,* 1982). In this region, the Burma plate is characterized by significant strain partitioning due to oblique convergence of the India and Australia plates to the west and the Sunda and Eurasian plates to the east. It is a typical oceanic-oceanic convergent plate boundary (Fig.11) where the Indian plate moving at a rate of 5 cm a year relative to the Burma plate came together, collided and the Indian plate dived (subducted) under the Burma plate (Fig.12). Volcanic eruptions are commonly seen at such convergent boundaries. "Two major plate tectonic features on either side of a narrow strip show how seismically active the region is."



(Source: USGS)

FIG 11. A typical Oceanic-Oceanic convergent plate motion

4.1.2 Lethal combination

A lethal combination of huge magnitude and shallow depth focus led to high vertical displacement of the Burma plate that acted like a great piston deforming the sea. The aftershocks within two hours at the Andaman islands following the main earthquake in the Burma plate have gone further to fracture and move the Burma plate boundary by 1000 km. That in essence is the power of the earthquake that struck off the Sumatra coast. The U.S.Geological Survey has called this event a mega thrust earthquake referring to the large cracking of the plate boundary.

According to them, mega thrust earthquakes often generate large tsunamis that can cause damage over a much wider area than is directly effected by ground shaking near the earthquake's rupture. Aftershocks are distributed along much of the shallow plate boundary between northern Sumatra (approximately 3°N) to near Andaman Island (at about 14°N).

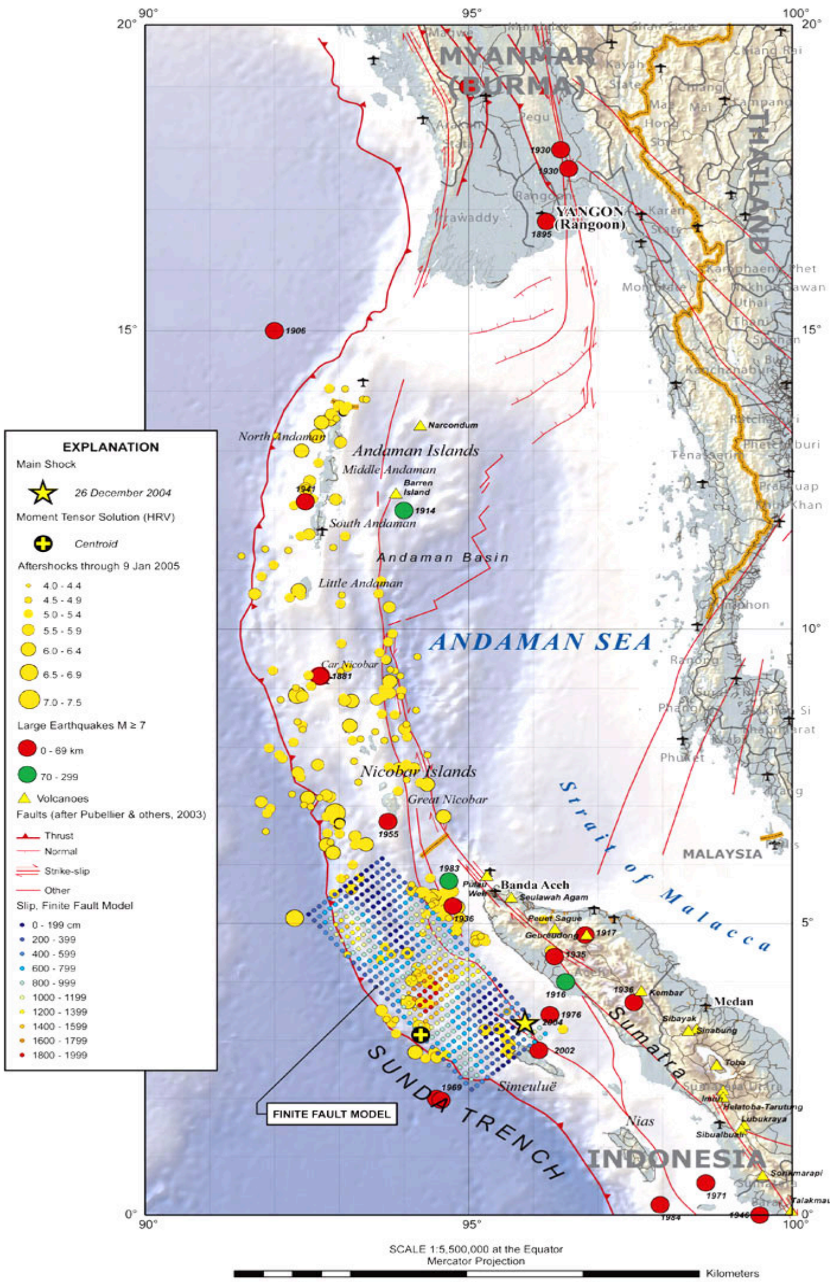


FIG 12. Base map of the Sumatra subduction zone showing seismicity associated with the 2004 earthquake (Source: USGS).

Shallow focus earthquakes measuring 6.5 can also cause tsunamis. But such tsunamis will die out after some distance. The vast expanse of the Indian Ocean posed little challenge to the movement of the killer tsunami. Reaching a distance of 2000 km to hit the Indian coast was not difficult. Perhaps giant tsunamis can travel as far as 5000 km. This was the first time that a tsunami of this magnitude had struck the Indian coast.

Since a large amount of pent-up energy in the compression zones along the plate boundaries has been released in the recent earthquake of 26th December 2004, it will take years for another incident of the same magnitude to recur. But countries in the Indian Ocean should pay more attention to earthquakes and tsunamis in the future.

5 Observations of December 26, 2004 Tsunami in India

5.1 Simulation results

A wave modelling generated by Active Fault Research Center, National Institute of Advanced Industrial Science and Technology, Japan highlights the crests and troughs of the tsunami waves as they travel across the Indian Ocean and refract around islands and interfere with each other (Fig. 13). A close observation of this modelling results infer that the Andaman and Nicobar islands were hit by strongest tsunami waves in no time after it generated at north off Sumatra. The tsunami hit eastern most point of Sri Lankan coast after 100 minutes, coasts of Orissa and Andhra Pradesh after 110 minutes and Tamilnadu coast after 120 minutes of its generation. It took more than 3 hrs to hit the western coast of India.

The propagation of tsunami waves is much stronger in east-west direction than north-south direction as the approximate fault of 1200 km length and 100 km width lies in near north-south orientation. As a result, strongest waves hit the coasts of Thailand, Indonesia and other nearby areas which are closely located on the east of the epicenter. The intensity of these tsunami waves that hit along the coastline of Orissa and Andhra Pradesh is weak due to their diagonal propagation. However, southern east coast of India and Sri Lanka experienced much stronger tsunami waves due to their location in mere western side of epicenter. Though the Palk Strait

and further southern areas of Tamilnadu are shadowed by Sri Lanka, the waves refract around island and inundated these coastal areas. The damage to Kerala coast on the west coast of India is also due to this wave refraction beyond Kanyakumari. The wave modelling by Institute of Geophysics and Planetary Physics, University of California also revealed similar results (Fig.14). According to this simulation, tsunami wave hit Chennai coast about 110 minutes after its generation and has got 1.4 m of run up.

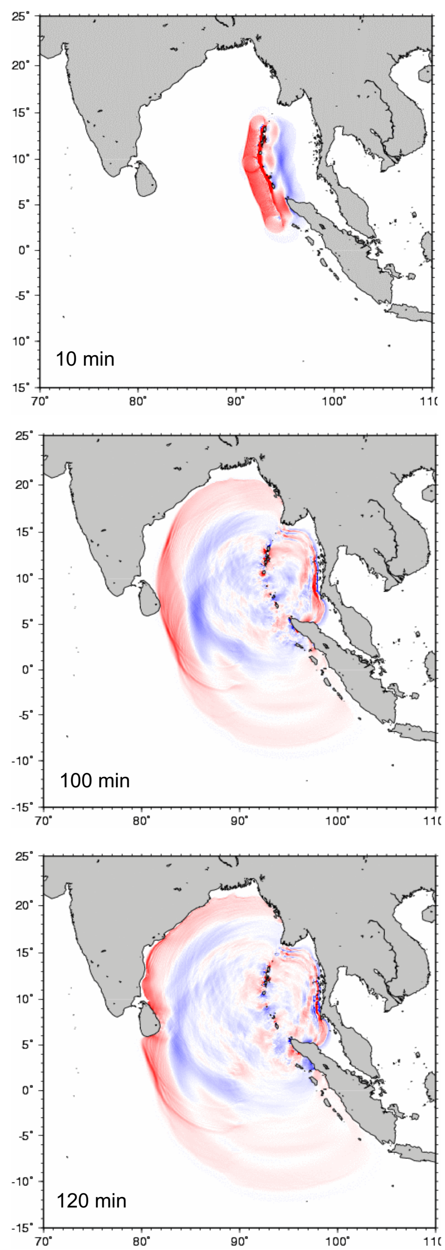


FIG 13. Visualisation of Tsunami Wave propagation across Indian Ocean.
The red color indicates the water surface is higher than normal, while the blue indicates lower (Courtesy: National Institute of Advanced Industrial Science and Technology, Japan).

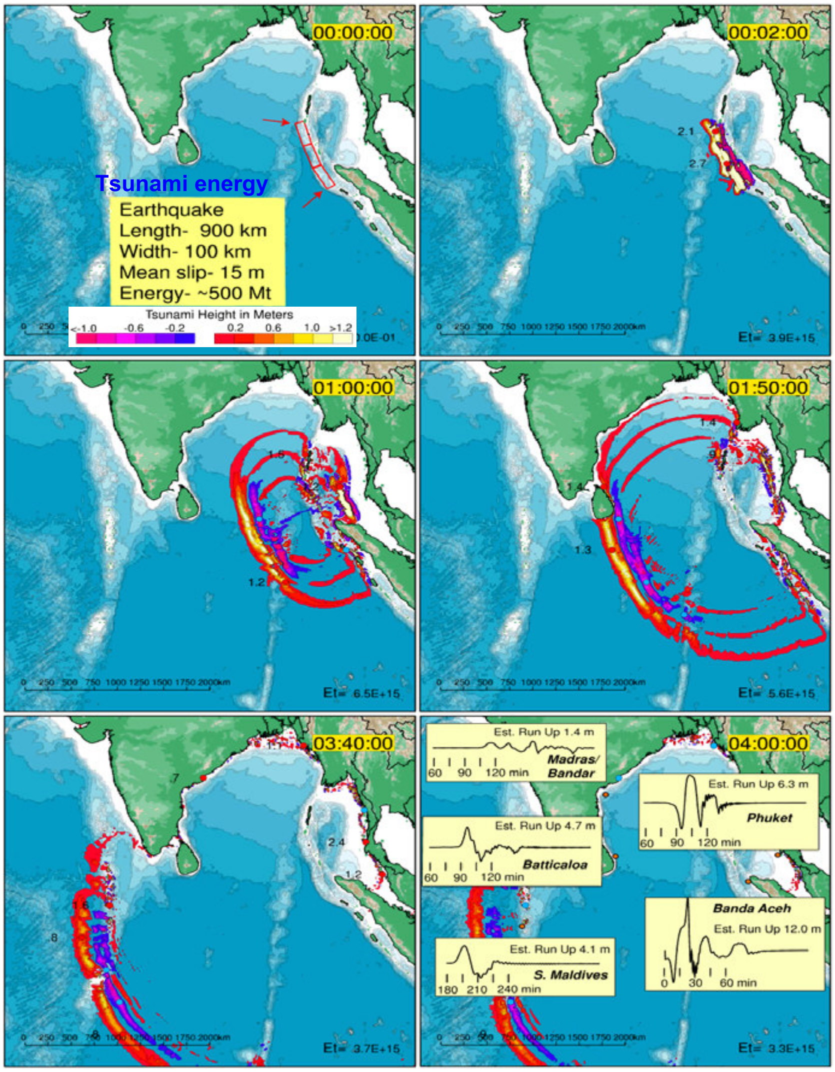
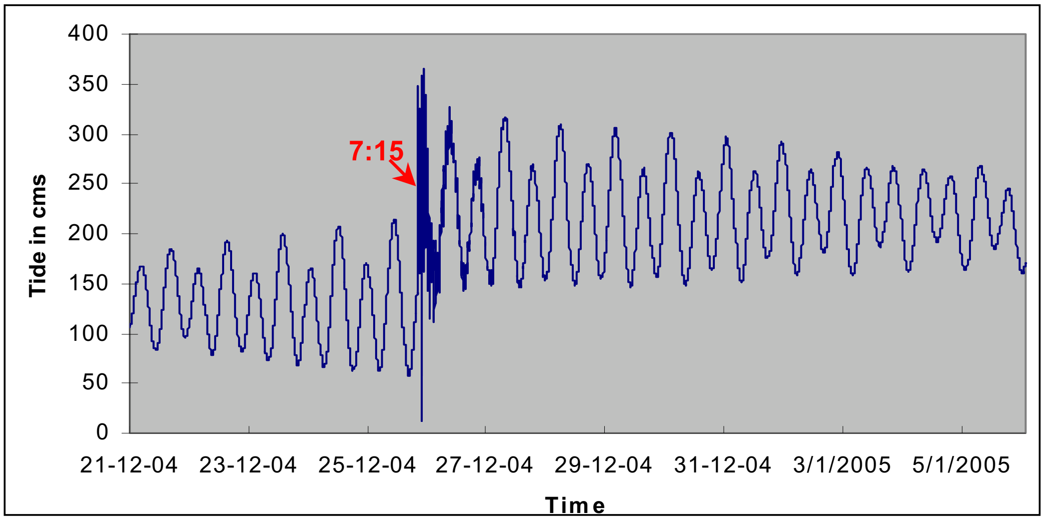


FIG 14. Simulation of Tsunami Wave propagation across Indian Ocean
(Courtesy: Institute of Geophysics and Planetary Physics, University of California)

5.2 Physical Observations

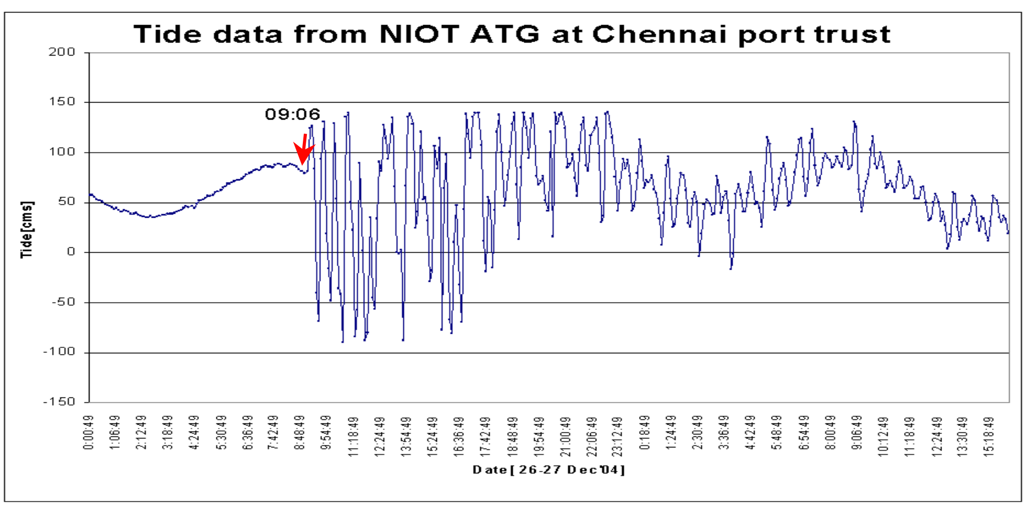
National Institute of Ocean Technology (NIOT), Chennai has deployed Acoustic Tide Gauges (ATG) at selected places along the Indian coast and Port Blair. The tide gauge at Port Blair, S.Andaman functioned normally till 06.50 hrs on 26th December 2004 and showed the tide level of 2.4 m. At 07:15 hrs tide gauge showed abnormally high water level of 3.48 m, an increase of water level by 1.0 m due to tsunami (Fig. 15). It is to note that the tide levels immediately after the tsunami are around 0.8 m, above the normal sea level. This may be due to the subsidence of the land in Port Blair. The tide levels recorded by Andaman harbour works in Port Blair at different jetties also seem to be showing tide level in excess of 0.8 m which confirm possible land subsidence to this extent.



(Courtesy: NIOT, Chennai)

FIG 15. Variation of Tide at Port Blair during Tsunami.

NIOT's ATG at Chennai has also recorded the first signal of tsunami in the form of "receding water" at 09:06 hrs at Chennai Port Trust followed by abnormality in tide level at 09:15 hrs on 26th December 2004 (Fig.16). The tide gauge was overwhelmed by the sudden and abnormally high water level and harbour oscillations due to which the tide record showed a saturation at around 1.5 m. However, the lower ranges clearly show that the water level should have been much above 1.5 m. The difference between the time of occurrence of tsunami at Port Blair, Andaman and Chennai is around 2 hrs and corresponds well with the distance between Chennai and Port Blair and the speed of the tsunami wave.



(Courtesy: NIOT, Chennai)

FIG 16. Variation of Tide at Chennai Port Trust during Tsunami

The Tide gauge data from major ports of India maintained by Survey of India has been processed by National Institute of Oceanography which showed that the tsunami hit Chennai at 09:06 hrs, Machillipatanam, Visakhapatnam and Paradip, at 09:05 hrs, Tuticorin at 09:57 hrs, along the east coast and on the west coast it hit Kochi at 11:10 hrs and Mormugao at 12:25 hrs (Fig.17). The non-tidal oscillations continued at Visakhapatnam, Tuticorin, Kochi and Mormugao well after the main event took place. NIOT's ATG at Kochi has also recorded first hit of tsunami at 11:12 hrs coincided with that of Survey of India tide gauge.

There were no reports of inundation of coastal areas due to tsunami in the northern Andhra Pradesh and Orissa as the water level rose by less than 0.5 m. However, the inland areas like Ports and Harbours, for example, Visakhapatnam Fishing Harbour and Port experienced amplification of tide due to coning effect from outer harbour to entrance channel and unusual current speed in the order of 5 to 10 m/s (Fig.18). These strong flood and ebb currents have forcefully pulled 15-20 fishing boats out of harbour (Fig.19); during the course few boats encountered minor damage.

Although Tuticorin is situated south of Rameswaram, Tamilnadu, it witnessed tsunami at 09:57 hrs, almost an hour later it hit Chennai coast. It is to notice that when high energy tsunami waves traverse horizontally across Indian Ocean, the east coast of Sri Lanka has absorbed the devastating tsunami energy and the refracted waves with low energy only reached its west coast and southern east coast of Tamilnadu, which is confirmed by the wave modelling studies (Figs. 13 & 14). Thus most of the southern coastal belt of Tamilnadu, shadowed by Sri Lanka, were less affected. It is for this reason, the refracted tsunami waves took more time to reach Tuticorin.

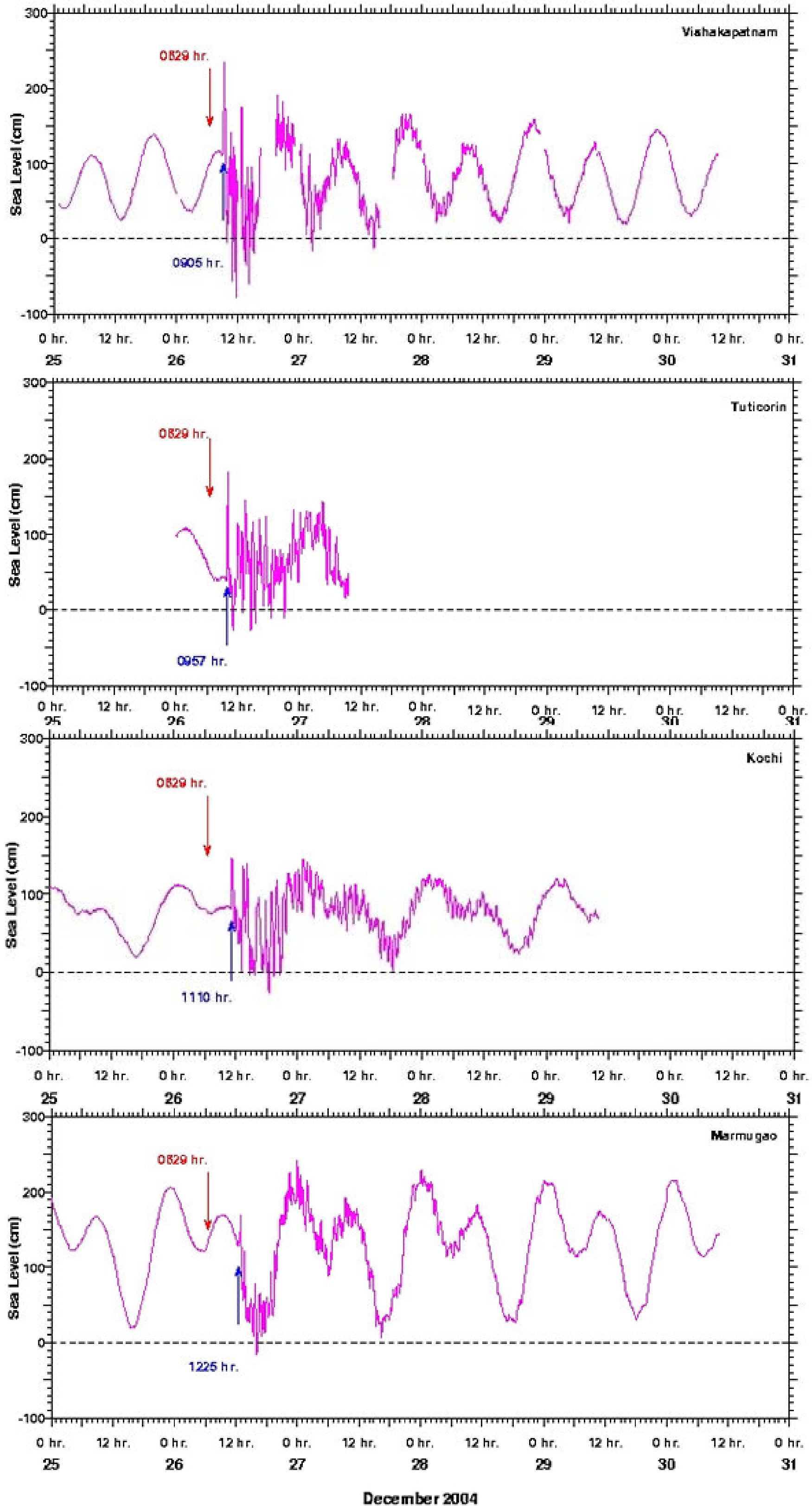


FIG 17. Observed Tide at different Ports showing the sea level changes on December 26, 2004.
Red arrow indicates the approximate time of occurrence of the earthquake off Sumatra and the blue arrow indicates the time of arrival of the disturbance at respective places. (Courtesy: Survey of India and NIO).

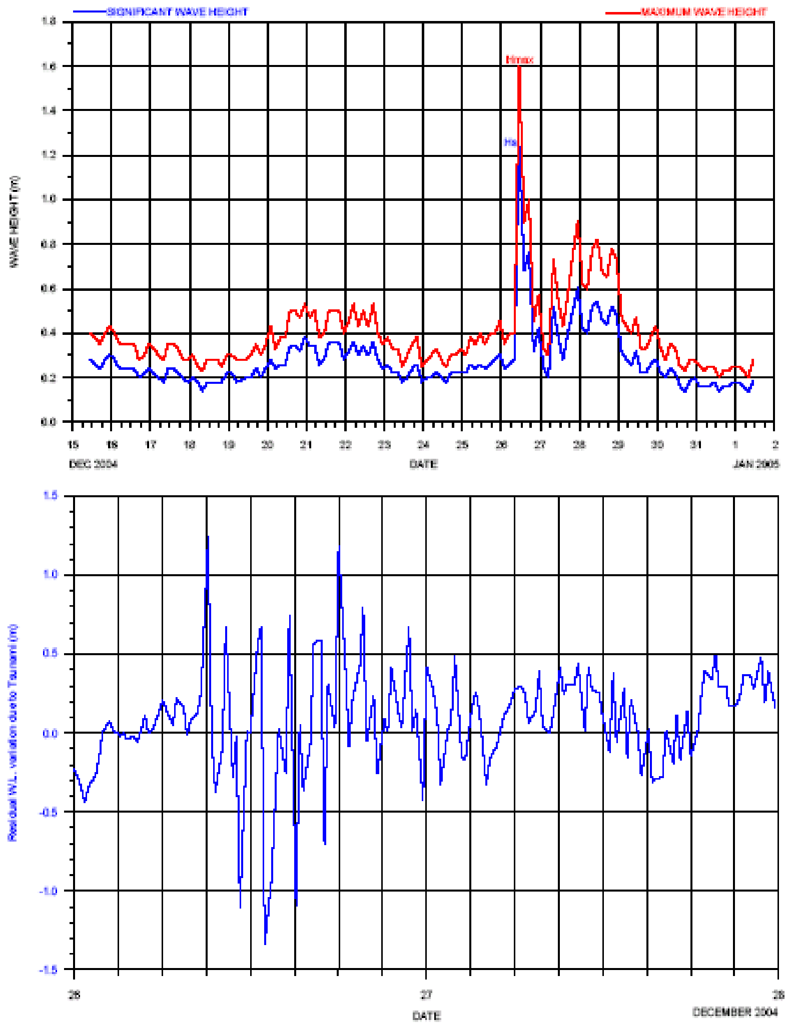


FIG 18. Variation of Wave height and Water level during Tsunami at Visakhapatnam Port (Courtesy: INDOMER, Chennai)

(Source: ICMAM-PD, Chennai)

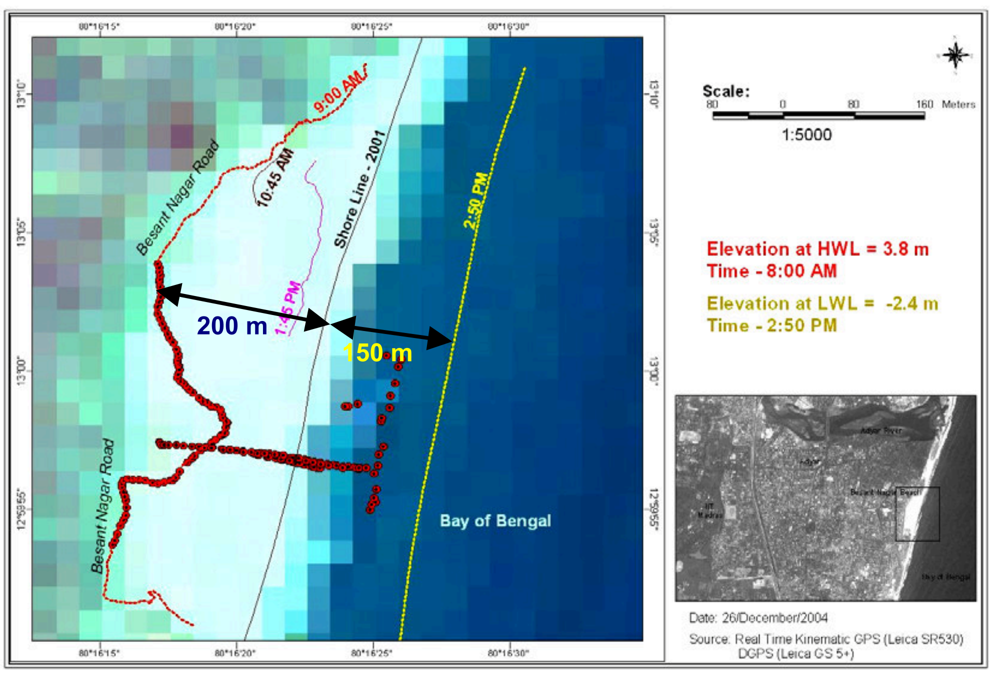
FIG 19. Boats pulling out of Visakhapatnam Fishing Harbour (VSH) by strong Tsunami ebb currents. VSH is one of the Hot Spot location of DOD's COMAPS programme and the strong currents churned the bottom sediments resulting black, muddy polluted ebb waters (in yellow circles).

5.3 Extent of Inundation along Tamilnadu and Andaman & Nicobar Islands - observations by ICMAM-PD, DOD, Chennai

The coast of Tamilnadu experienced different levels of impact with northern and southern coastal belt showed less human loss of about 8000 people.

5.3.1 Chennai coast

A team of scientists from ICMAM-PD visited Besant Nagar Beach in Chennai immediately after hearing the first hit of tsunami to Chennai at 09:00 hrs and monitored the water level fluctuation from 10:00 hrs to 18:00 hrs on 26.12.2004 using sophisticated Real Time Kinematic GPS (Leica SR530, having accuracy of 1 cm for position and 15 cm for elevation) and DGPS (Leica GS5+) and analysed the impact of tsunamis. Figure 20 shows the extent of seawater excretion over a period of time.



Data: ICMAM-PD

FIG 20. Variation of Water level at Besant Nagar beach, Chennai on 26.12.2004.

At 09:00 hrs as the tsunami hit the Chennai coast, water excursed to a maximum of 200 m inside the beach (up to kerb wall of the beach) with a surge height of 2.5 m.

Subsequently a series of waves hit the coast at 10:45 hrs, 12:30 hrs, 15:10 hrs and 17:10 hrs and the sea level returned to the original level around 18:30 hrs. At 14:50 hrs water line receded by 150 m from the original shore (Fig.21). The observations revealed that the run-up height at Chennai is about 3 m. This contradicts the estimated run-up height of 1.4 m at Chennai by Institute of Geophysics and Planetary Physics, University of California (Fig.14) indicating that their model needs further calibration with regional data.

FIG 21. Visuals of water level change during Tsunami at Besant Nagar beach, Chennai
Scientists of ICMAM-PD making observations using RTK and DGPS.

Elevation of beach/land and presence of sand dunes are controlling factors for water excretion and extent of damage caused by the waves. Marina beach, a few centimeter above mean sea level, experienced maximum inundation. About 1.8 km^2 of coastal area between Adyar and Cooum rivers along Chennai coast is inundated. The sea water excursed up to 590 m at Foreshore estate (Adyar river side) and 480 m at MGR memorial (Cooum river side) with a narrow excursion of 290 m at mid-stretch (Fig.22). The series of tsunami waves had a positive effect on Adyar and Cooum rivers, which are sewage carriers, whose mouths closed for most part of the year due to sand accretion, got opened, though temporarily, due to which these heavily polluted waters with sludge were flushed out to a great extent (Fig.23) which

might be having significant impact (but temporarily) on the water quality and biota of adjoining coastal environment. This can be clearly seen by the occurrence of bacteria up to or beyond 10 km offshore after tsunami when they were sighted at a maximum distance of 3 km offshore before tsunami at selected locations (Table 3).

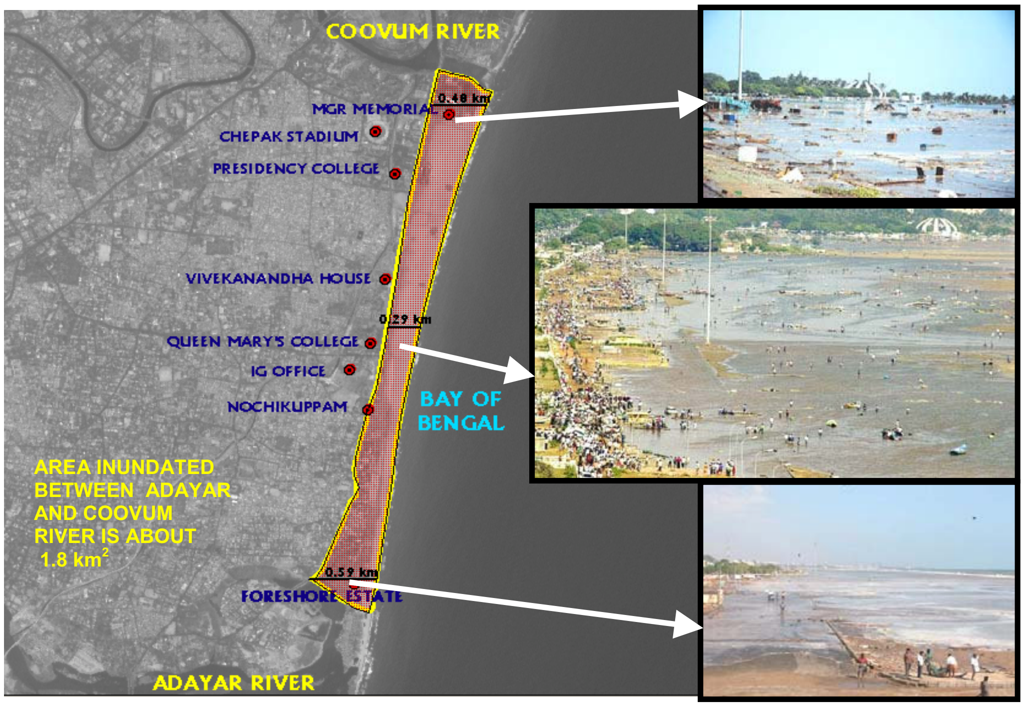


FIG 22. Extent of inundation at Chennai coast during Tsunami

(Source: CAS in Marine Biology, Parangipettai)

FIG 23. A view of polluted waters of Cooum river flushed out due to opening of mouth as a result of Tsunami

TABLE 3. Distribution of Bacterial population before and after Tsunami along Tamilnadu coastal waters

Bacteria	Before Tsunami		After Tsunami	
	Stations	Distance (km)*	Stations	Distance (km)*
THB (Max)	All stations	0.5, 1 & 3	Pondy	10
E.Coli & Faecal coliform	All stations	Hot Spots & 0.5	Ennore	10
Salmonella LO (Max)	Tuticorin & Chennai	0.5, 1 & 3	Nagapattinam	10
SFLO (min)	Ennore coast	0.5 & 1	Ennore	3 & 5
Water/ Sediment	All stations	Water low/ Sediment high		Water & sediment slight variation

* distance from the coast. (Source: CAS in Marine Biology, Parangipettai)

5.3.2 North Chennai between Ennore and Pulicat

Observations made along the north Chennai coast (Fig.24) indicated that the water level at Ennore creek rose by a maximum of 5 m and water excursed up to 300 m at the adjoining coast. Though the Katupallikuppam fishermen settlement, located 6 km north of Ennore Port and 190 m away from the coast has escaped without any damage due to their occupation on a sand dune, the sea water inundated to about 500 m in low lying areas around the village. Further north, the Kalanji fishing hamlets were not affected by waves as the inundation is seen only up to 45 m. Tsunami in one way benefited the Pulicat Lake by wide opening its mouth, but its fishing community, except a beach hamlet, is least affected due to presence of sand dunes. The above observations indicated that the extent of inundation decreased from Ennore to Kalanji due to the presence of shoals at north of Ennore Port, which acted as "wave dampers" in reduction of wave energy (Fig.24). Though this coastal belt is prone to accretion/erosion due to construction of Ennore Port, the ongoing studies of ICMAM-PD revealed that these shoals are acting as a natural barrier to the wave energy thereby controlling the intensity of erosion at north of Ennore Port. They also predicted that by considering the dimensions of these shoals, they may last for another few years. If the damage occurred to these shoals due to tsunami is significant, it will have considerable impact on the extent of their natural protection

to this coast. In view of this, ICMAM-PD will soon undertake the monitoring of these shoals to ascertain the extent of damage to them due to tsunami.

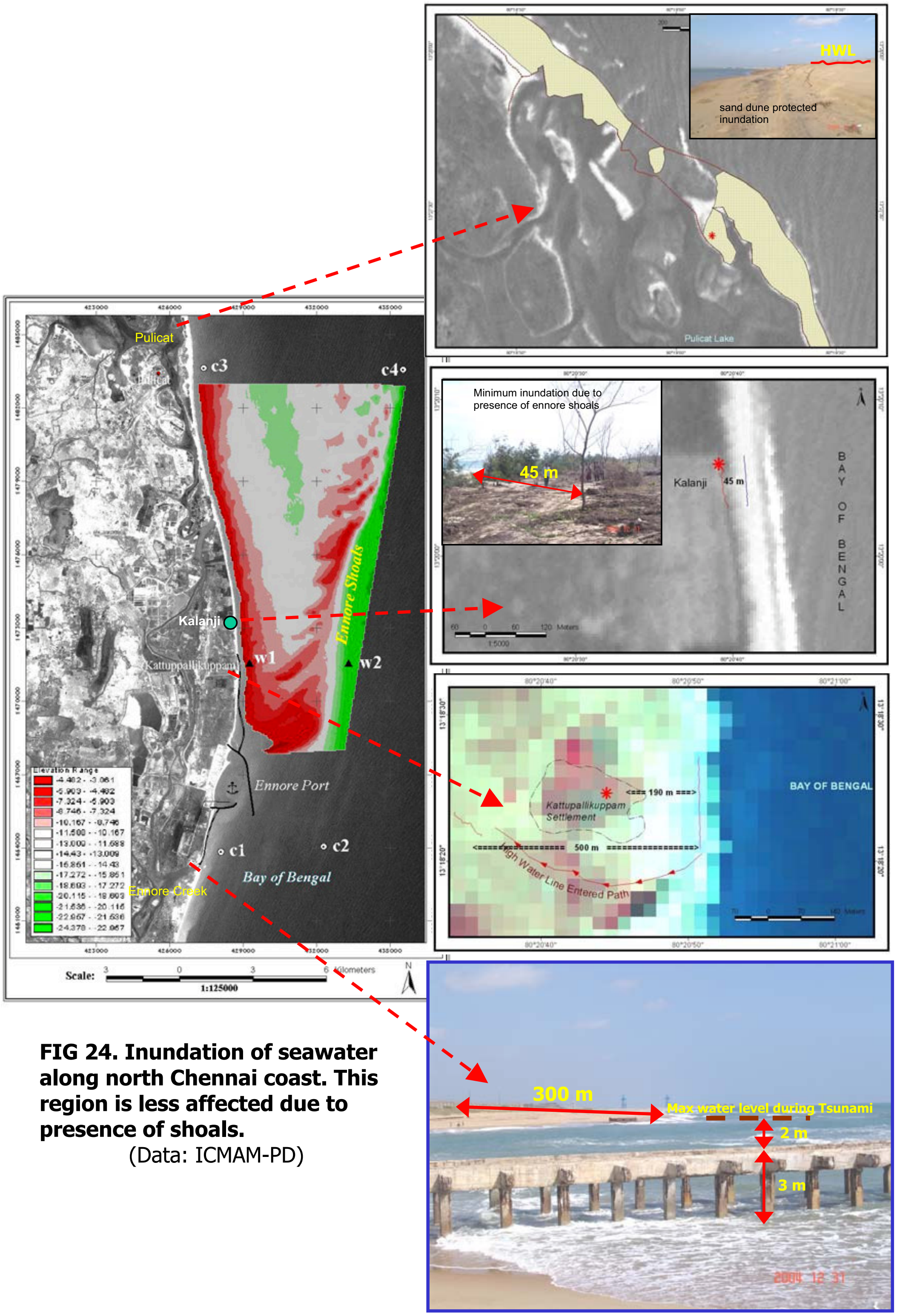


FIG 24. Inundation of seawater along north Chennai coast. This region is less affected due to presence of shoals.
(Data: ICMAM-PD)

5.3.3 South of Chennai

The preliminary results indicated that the southern Chennai upto Mahabalipuram along east coast road has not been affected much due to steep land elevations and the maximum inundation is seen up to 250 m. Presence of sand dunes and plantations at most of the locations played a vital role in protection of coastal villages in this area. However in the Kalpakkam area where the Nuclear Power Plant is situated, the terrain is nearly flat and slightly elevated above mean sea level, greater inundation is seen in this zone. The experience of coastal inundation between Pulicat and Kalpakkam due to this tsunami is that if CRZ is strictly implemented in this belt, there would not have been much loss to property and lives.

A death toll of about 500 is reported from the coastal area of Cuddalore with an inundation of 1.5-2.0 kms at Devanampattinam coast mainly due to successive wave propagations through the back waters. Severe damage is also noticed to fishing boats of this area. Further south of Cuddalore, the areas adjoined to the river mouths of Vellar, Chinna Vaikal (Pichavaram) and Coleroon were severely damaged claiming more than 1000 lives. The Parangipettai village (adjacent to Vellar river) witnessed maximum inundation up to 2.5 kms as the initial terrain slope (from coast) is very gentle and far reaching areas are low lying. The areas adjoined to Vellar inlet and its back waters which were marked as a green region with dense plantation acted as a barricade to tsunami waves which resulted in reduction of wave energy, otherwise the intensity of the damage could have been much more severe. The satellite images before and after tsunami of this region clearly explain this bio-shielding effect wherein the loss of vegetation after tsunami can be noticed (Fig.25). The Vellar inlet which is having two openings each of about 290 and 235 m width as observed by a team of scientists from ICMAM-PD and IIT, Chennai on 24.12.04, a day before tsunami occurred was made opened to a great extent by tsunami waves resulting the seawater ingression up to 5 km inside. The satellite imageries of these mouth inlets before and after tsunami are presented in Figure 26. The flow of tidal waters inside the estuary has inundated the paddy fields with seawater.

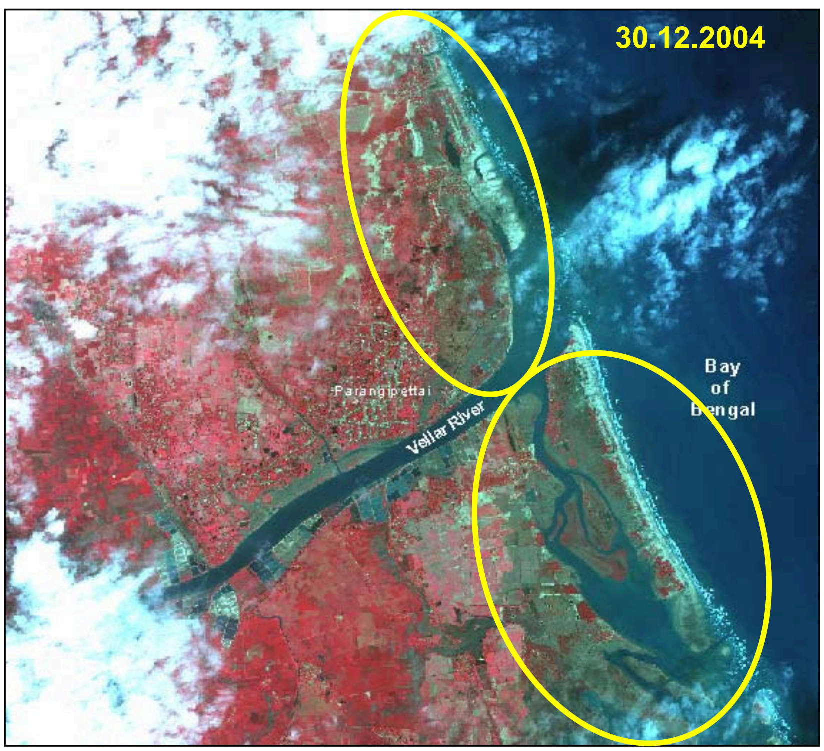
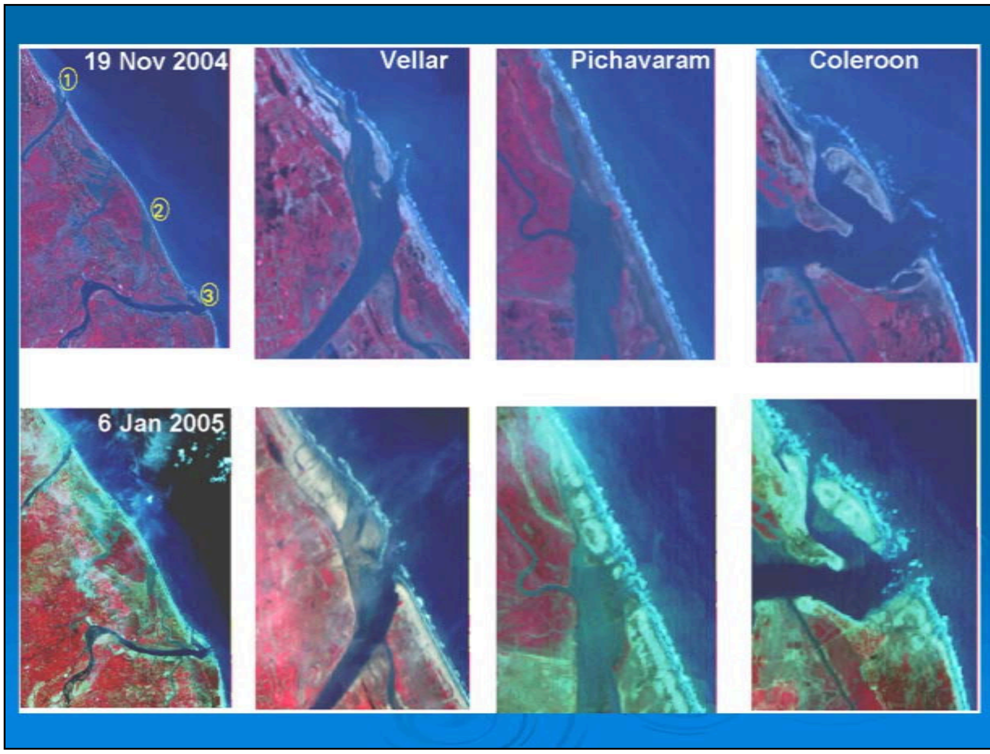


FIG 25. Loss of vegetation in and around Vellar inlet (in yellow circles) showing the bio-shielding effect to Tsunami waves.



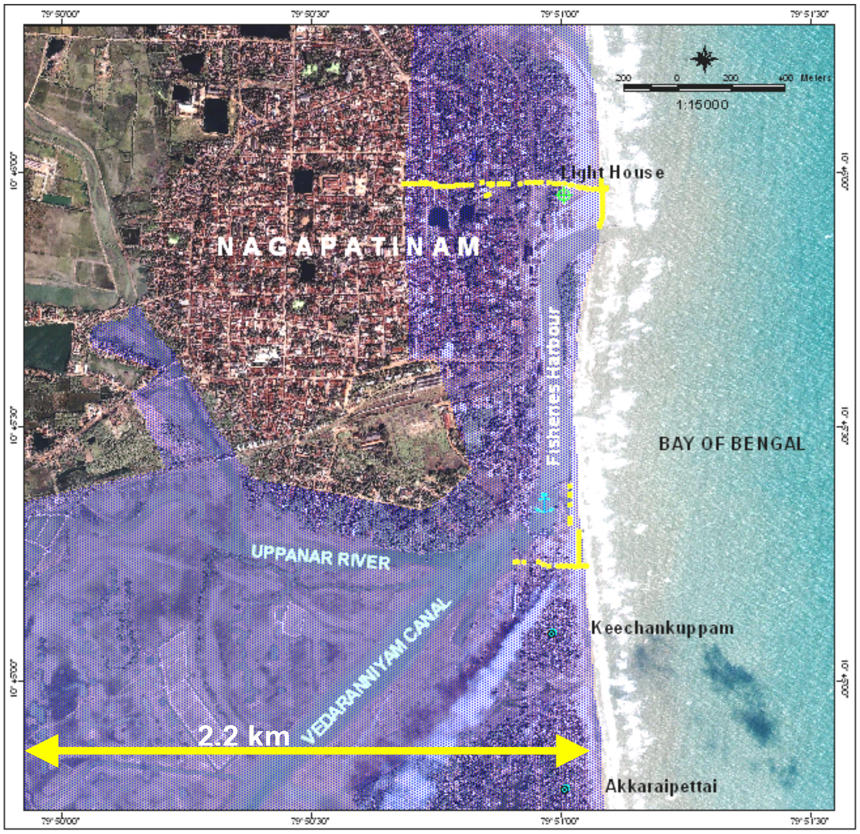
A)

FIG 26. Satellite imageries before and after Tsunami showing the extent of opening to various inlets of Pichavaram area. (Source: NRSA)

5.3.4 At Nagapattinam

Nagapattinam, a coastal town, located about 400 km south of Chennai is the worst affected place in India due to tsunami claiming more than 6000 death toll and extensive damage to the public and private property. It is believed that the dual wave effect (straight waves plus diffracted waves from Sri Lankan coast), gentle slope of continental shelf and gentle elevation of hinterland coupled with the presence of Uppanar river and Vedaraniyam canal in the southern side triggered the deadliest impact of tsunami waves. The preliminary observations revealed that the impact on the southern part is deadliest than northern part due to the presence of these water bodies through which the successive progression of tsunami waves pushed the waters to distances beyond 2 km towards landside (Fig.27). However, the runup level in the northern part of Nagapattinam near Light House is close to 4 m with a maximum inundation up to 755 m from the coast (Fig.28). Despite presence of wide beach (~200 m), the gentle land topography facilitated landward intrusion of seawater up to 800 m. Because of this, the high energetic waves crossed the beach and flooded the human settlement. Severe damage has been noticed to

hundreds of fishing boats, several acres of agricultural land and also to beach tourism (Fig.29).



(Image courtesy: Space imaging)

FIG 27. Extent of inundation of seawater in Nagapattinam due to Tsunami.

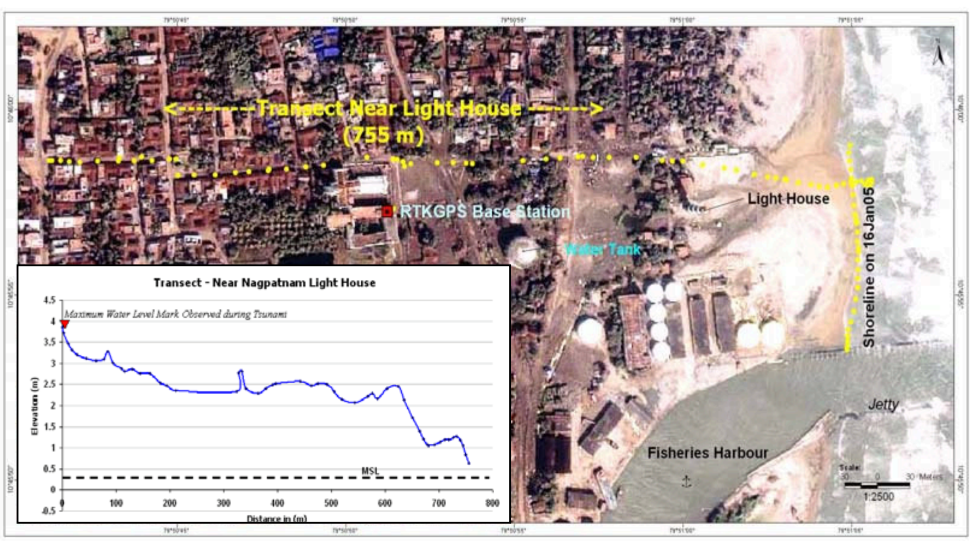


FIG 28. Extent of inundation in north Nagapattinam due to Tsunami
(Image courtesy: Space imaging; Data source: ICMAM-PD, Chennai)

FIG 29. Glimpse of damage occurred in Nagapattinam.

5.3.5. Tsunami in Andaman and Nicobar islands and observations on run up levels

The Andaman and Nicobar islands located in the subduction zone of Burma Plate is classified as Seismic zone 5 indicating high level of risks due to earthquake (Fig. 30). Tsunami waves hit the Nicobar group of islands within few minutes and reached Port Blair in South Andaman at 07:15 hrs (Fig.15), immediately after its generation at 06:45 hrs at Sumatra, indicating the traveling speed of about 700 km/hr. The waves transformation varied at different locations (depending on the coastal geomorphology) and the tips of islands faced more fury of tsunami waves.

The Nicobar group of islands namely Great Nicobar, Katchall, Teressa, Nancowry, Trinkat, Car Nicobar etc. were severely affected by tsunami waves as they are closer to the epicenter and also smaller in nature surrounded by the sea all around. The impact on Andaman group of islands were less except on Little Andamans due to their geometry and nature of topography (Fig.30). Since the settlement in South Andaman islands is largely confined in sheltered areas like bays and they are far from the coast and more importantly the settlement areas are in elevated areas except in certain low elevated far inland locations like Sippighat area, there were almost no loss of life, but damage to properties especially to fishing vessels were

considerable. The extent of loss of life in A & N islands due to tsunami is given in Table 4.

Table 4. Death toll in A & N islands as of 23.1.05 due to Tsunami

S. No	Islands	Population on (2001 census)	Dead	Missing	Persons in camp*
NICOBAR DISTRICT					
1.	Car Nicobar	20292	790	348	15550
2.	Teressa	2026	50	9	3296
3.	Katchal	5312	345	4310	1818
4.	Nancowry	927	1	2	934
5.	Camorta	3412	51	387	1476
6.	Great Nicobar	7566	336	219	4690
7.	Other Islands of Nicobar (evacuated)	2533	288	266	--
	Sub-total	**42068**	**1861**	**5541**	**27764**
ANDAMAN DISTRICT					
1.	Andaman includes, Port Blair	181949	5	--	2833
2.	Little Andaman	17528	56	14	6569
3.	Other Islands of Andaman	114607	3	--	5000
	Sub total	**314084**	**64**	**14**	**14402**
	Total (UT)	**356152**	**1925**	**5555**	**42166**

* includes persons from other affected islands. (Source: A & N Administration)

The inundation of seawater into the land with high velocity and their retreat with same or higher velocity cause extensive damage to human life and property. As said extent of inundation is measured in term of vertical run-up (Fig.4). The extent of vertical run-up of seawater depends on nearshore bathymetry, beach profile, land topography and velocity of tsunami waves and their frequency. Due to these parametric variations in Andaman and Nicobar islands, the run-up level and landward penetration characteristics of seawater varied from one location to the other within an island. The geometry of the islands and existence of offshore barriers like islets, trenches also play a role in the landward propagation of tsunami waves. Keeping these issues in mind and in order to get an idea on run-up levels, they were measured at a few selected locations which are considered to be representative.

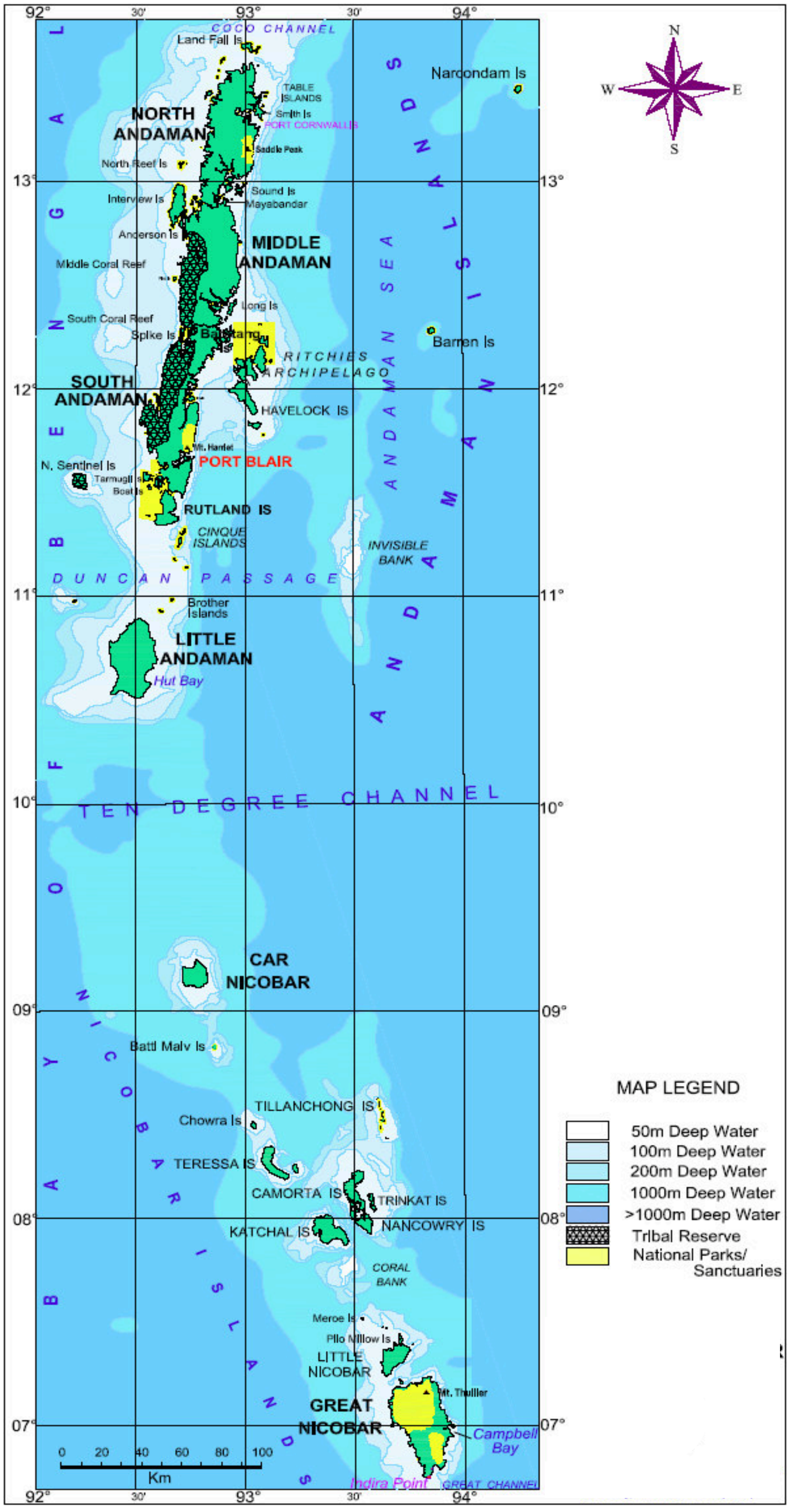


FIG 30. Andaman and Nicobar group of islands
(Map by ANCOST, NIOT)

Due to logistics and other constraints, the measurements were restricted to north Andaman, Great Nicobar, Car Nicobar, Port Blair and Little Andamans.

A team of Scientists of Integrated Coastal and Marine Area Management (ICMAM) Project Directorate of Department of Ocean Development, Chennai assisted by Scientists from Andaman and Nicobar Centre for Ocean Science and Technology (ANCOST) of NIOT conducted run-up measurements in Andaman and Nicobar islands from January 18 - February 5, 2005. The locations were selected based on local enquiry. Elevations at clearly visible seawater mark on building/ structures were taken as the Run-up levels for measurements. Table 5 gives the details of measured run-up levels which have been corrected to Mean Sea Level (approx. 0.8 m added to existing MSL to accommodate the land subsidence occurred during earthquake). Figures 31 to 33 show locations at where measurements were made and elevation profile of certain areas.

TABLE 5. Run-up level of sea water during Tsunami in Andaman & Nicobar Islands

Location	Maximum run up level (m)	Distance up to which seawater inundated inland (m)
South Andaman (Port Blair)		
JNRM College, Aberdeen	2.9	130
Bamboo Flat	3.5	250
New Wandoor	3.7	215
Wandoor	3.9	215
Chidiyatopu	4.5	130
Chouldari	2.0	250
Sippighat (Creek)	2.0	2000
North Andaman		
Diglipur	1.5	100
Rangat	1.5	200
Little Andaman		
Hut Bay	5.0	1200
Car Nicobar		
Malacca	7.0	1000
Air base	7.0	1100
Great Nicobar		
Campell Bay (central)	3.0	300
Campell Bay (South)	6.0	50

Data: DOD ICMAM Project Directorate, Chennai

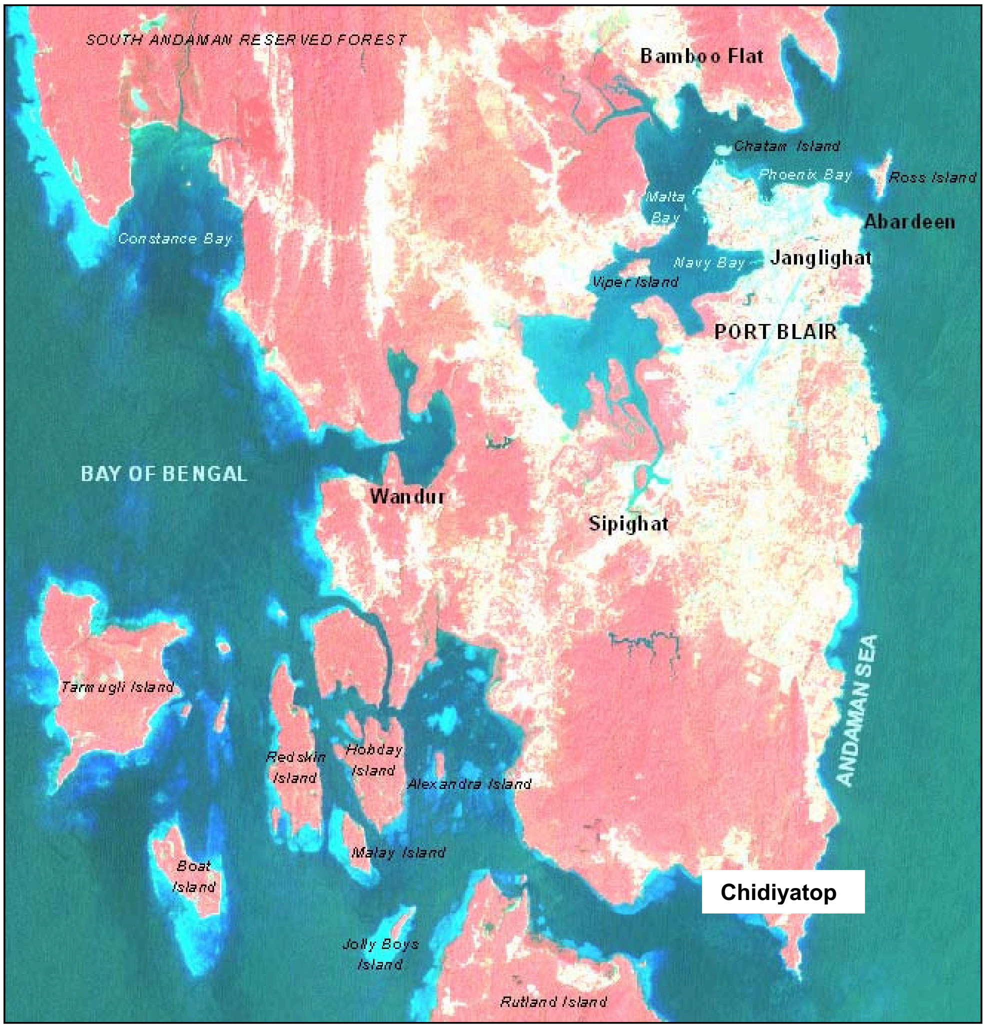
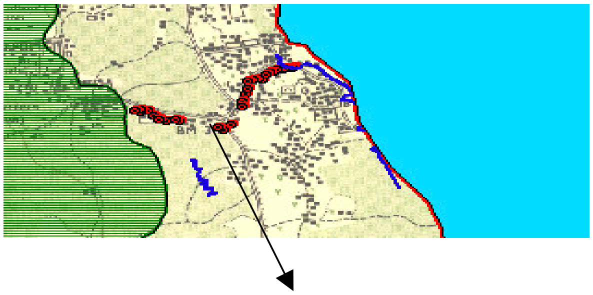
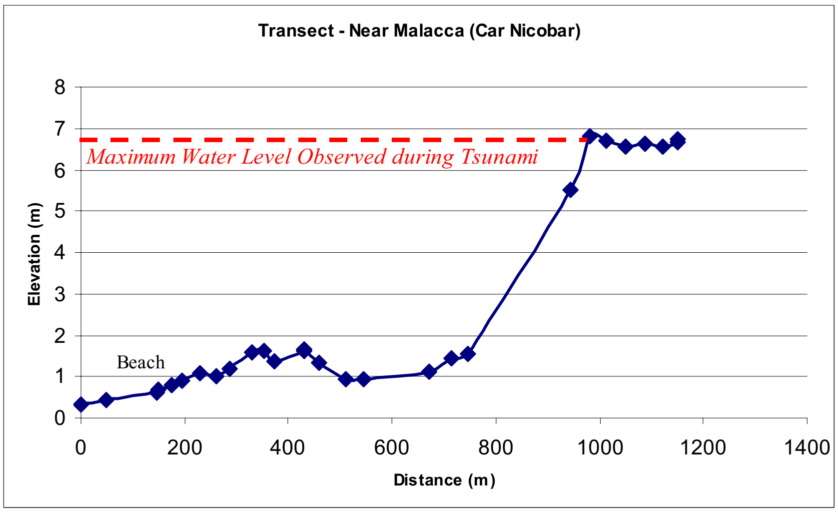
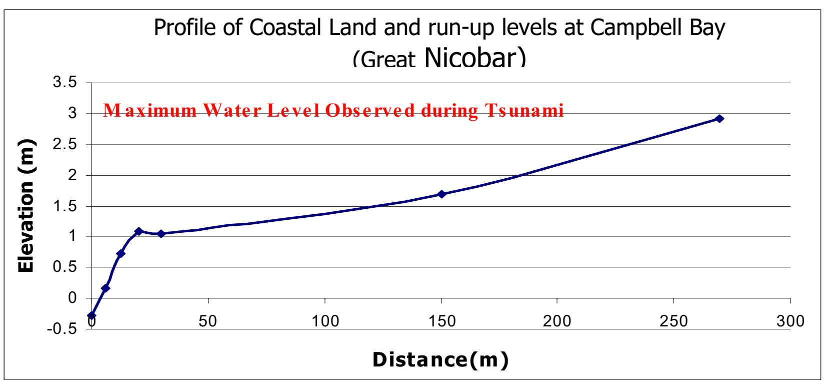


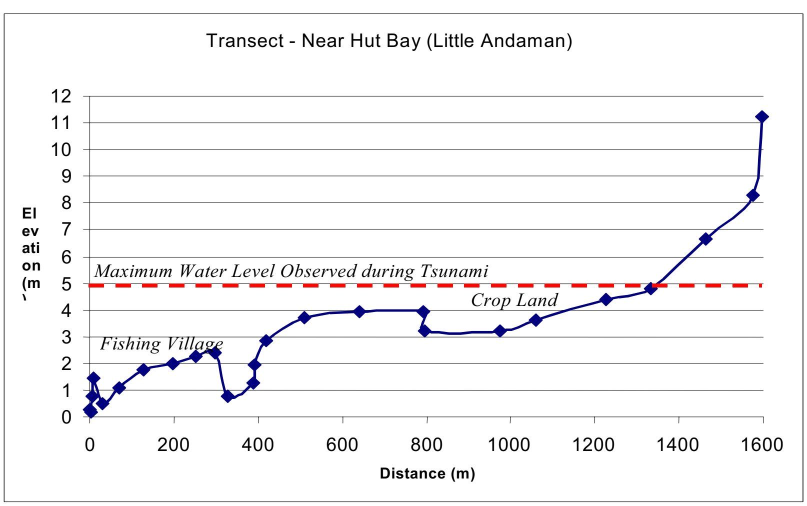
FIG 31. Few locations of run up measurements in and around Port Blair

FIG 32. Map indicating Hut Bay in Little Andamans




Transect - Near Malacca (Car Nicobar)
Maximum Water Level Observed during Tsunami
Beach
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
200
400
600
800
1000
1200
1400


Profile of Coastal Land and run-up levels at Campbell Bay (Great Nicobar)
Maximum Water Level Observed during Tsunami
Elevation (m)
Distance(m)
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
50
100
150
200
250
300


Transect - Near Hut Bay (Little Andaman)
Maximum Water Level Observed during Tsunami
Fishing Village
Crop Land
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
200
400
600
800
1000
1200
1400
1600

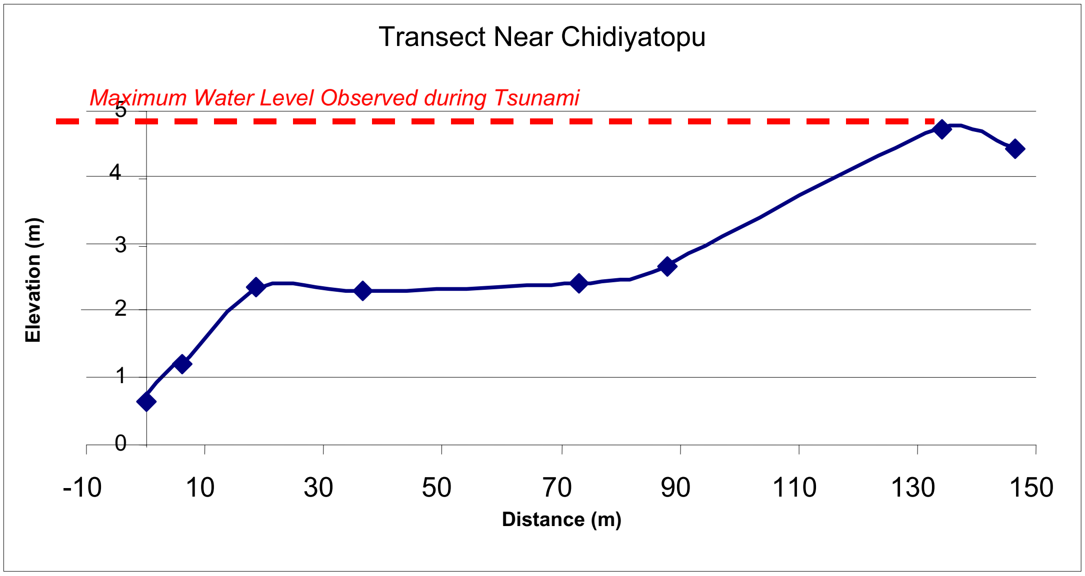


Fig.33 Graph showing run up levels with land profile

The National Remote Sensing Agency (NRSA) through IRS-1D LISS III image and other satellites has estimated the area affected due to tsunami (area inundated) in few Nicobar islands and the details are shown in Table 6 and Figures 34-36.

TABLE 6. Satellite based data on inundation of seawater in islands during Tsunami.

S. No.	Island name	Population (2001 census)	Geographical Area (ha)	Villages affected	Area affected (ha)
1	Trinkat	432	3630	4	360
2	Camorta	3412	18820	20	665
3	Nancowry	927	6690	9	26
4	Katchall	5312	17440	13	1432
5	Little Nicobar	353	15910	20	235
6	Great Nicobar	7566	104510	29	993

(Data source: NRSA)

IRS-P6 AWiFS Image of 21st Dec. 2004 | IRS-P6 AWiFS Image of 26th Dec. 2004 | IRS-P6 LISS- III Image of 4th Jan 2005

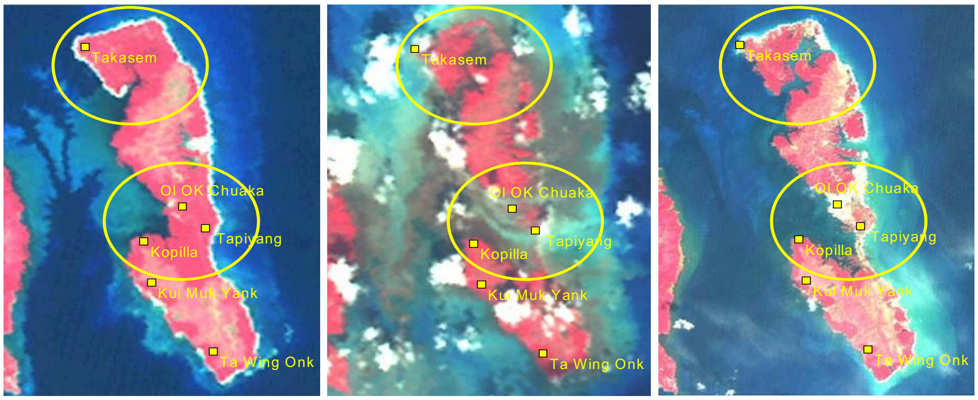


FIG 34. Pre and post Tsunami flooding of sea water in the Trinkat island (Source: NRSA)

Plate-8

IRS-P6 AWiFS Image of 21st Dec. 2004 | IRS-P6 AWiFS Image of 26th Dec. 2004 | IRS-P6 LISS III Image of 4th Jan. 2005

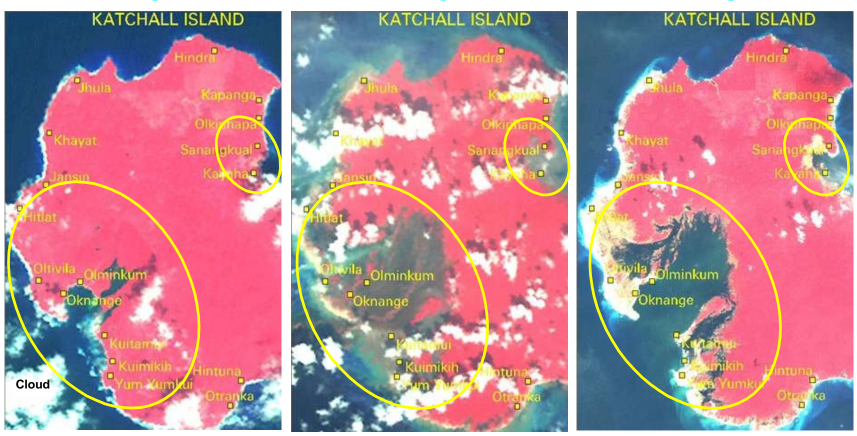


FIG 35. Pre and post Tsunami flooding of seawater in the Katchall island (Source: NRSA)

IRS-1D LISS III Pre-Tsunami image of 24th Dec. 2004 **SPOT Post Tsunami MLA = PLA merged image of 2nd Jan. 2005**

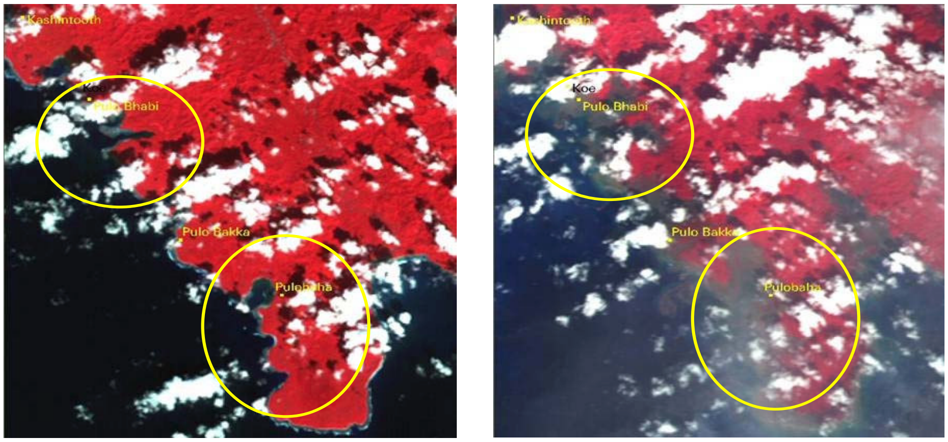


FIG 36. Pre and post Tsunami flooding of seawater in the Great Nicobar (Source: NRSA).

The satellite based data indicate that Great Nicobar, Trinkat, Katchall and Camorta were the worst affected (Table 6). Smaller the islands more vulnerable for natural hazards like tsunamis. The run-up level results (Table 4) clearly indicate that the mid sea islands like Little Andaman, Car Nicobar have less elevated areas along the coast, had inundation up to 1 to 1.2 km with the run up level reaching up to 7 m. The Port Blair area which contains mostly bays and creeks had lower run up levels except that of Chidiyatopu. In case of Chidiyatopu the run-up level of 4.5 m is mainly due to its geographical location i.e. a tip of South Andaman facing tsunami wave direction in the Andaman sea. Within the Port Blair area, it has been observed that the low lying areas like Sippighat, the penetration of sea water from the creeks were as much as 2 km inland due to gentle increase in the slope (run-up level being 2 m). The Sippighat area which supports agriculture has several low lying agricultural fields. The rain water during the monsoon months are drained through sluice gates and during the low tide these waters reach the adjoining creek/bay. The north Andaman areas that were less affected by the tsunami recorded run up levels of 1.5 m with the seawater intruding up to 200 m (Table 5).

The earthquake occurring at a magnitude of Ms 8.6 has felt to have caused land subsidence in South Andaman and Nicobar Group of islands. This is being investigated by Survey of India. Even though the precise estimates on the extent of subsidence is not available, the chart datum in the tide gauge records clearly indicate

the possibility of land subsidence to the extent of 80 cm at Chattam island near Port Blair (Fig. 31). This is in conjunction with the tide levels above 0.9 m of normal sea level at Chatam island immediately after the earthquake (Fig.15). The measurements on elevation made using RTK at the jetties of Chattam island and Campbell bay after the tsunami were compared with the Andaman Lakshadweep Harbour Works bench marks available for these locations prior to tsunami. The results indicated rise of sea level to the extent of 1.3 m at Campbell bay and 1 m at Chattam which indicate possible land subsidence to this extent at these locations. Similar measurements made at Aerial Bay (Diglipur) and Rangat revealed possible evidence of retreat of sea level to the extent of 0.8 to 1 m in Aerial bay and 0.4 to 0.6 m at Rangat.

Such a possibility is evident from the high tide water entering into the paddy fields of Sippighat area that never occurred before. Inundation of inland low lying areas during the high tide has become a cause of concern for inhabited population as their houses are marooned with salt water. The concern is likely to increase during the monsoon months when the rain water antagonises movement of high tide water. The net effect would depend on the velocity of rain water flowing from low lying areas through sluice gates to the adjoining bay. If the tidal water dominates, the rain water tends to accumulate in all low lying areas and both the freshwater and sea water would increase the height of water level and likely to spread to the neighbouring elevated areas too.

5.4 Tsunami Magnitude

It is customary to report tsunami magnitude (Mt) based on tsunami wave height vis a vis epicentral distance. Abe (1979) has worked out a formula based on his extensive studies in Pacific Ocean for regional tsunami (100 km $< \Delta >$ 3500 km) and following relation is suggested (Abe, 1981):

$$Mt = \log H + \mathrm{Log}\,\Delta + 5.8$$

Where H is the maximum tsunami-wave amplitude measured by tide gauges in meters and Δ is the epicentral distance vis a vis Tsunamigeneic earthquake.

Considering the reported maximum tsunami wave height of 3.2 m at Chennai (Δ 2053 km), the tsunami magnitude (Mt) is worked out to be 9.6.

Similarly for Port Blair at epicentral distance of 990 km and reported wave amplitude of 4.5 m, the Mt is worked out to be 9.4. Pending precise information on amplitude of tsunami at different locations and average values in different coastal sectors the Mt for the current tsunami is tentatively fixed at 9.5.

5.5 Run-up level and beach profile changes along Kerala coast - by CESS, Trivandrum

The December 26, 2004 tsunami had a devastating impact on the Kerala coast too. The locations of Kerala coast affected by the tsunami are shown in Figure 37. Though this coast was in the shadow with respect to the direction of propagation of the tsunami waves, it had its access to the Kerala coast, obviously due to the processes of refraction, diffraction and reflection. Its destructive power left nearly 200 people killed and hundreds injured in addition to the loss of houses and properties worth several crores of rupees. The highest toll was reported from Kollam district followed by Alappuzha and Ernakulam districts. A large number of fishing boats and implements were washed away as tidal waves hit the coast. Hundreds of families had been shifted to relief camps as police, fire force and medical personnel swung into relief operations.

A team of Scientists from CESS, Trivandrum have conducted field visits all along the Kerala coast and estimated the run-up level along the shore and beach profile changes at the worst affected areas of the coast. For estimation of run-up level, the field signature such as trapped floating objects in plants/trees/buildings and information collected from local populace were relied upon. The beach profile and volume changes were measured for the worst affected regions of the Kollam and Alapuzha districts where the pre-tsunami beach profile changes were available.

Fig 37. Locations of Kerala coast affected by Tsunami. The size of the circles indicates the relative severity of the damage.

5.5.1 Run-up level along the Coastal Zone of Kerala

The run-up levels for different stretches of Kerala coast are presented in Figures 38-40. The run-up levels given are with reference to the mean water level at each

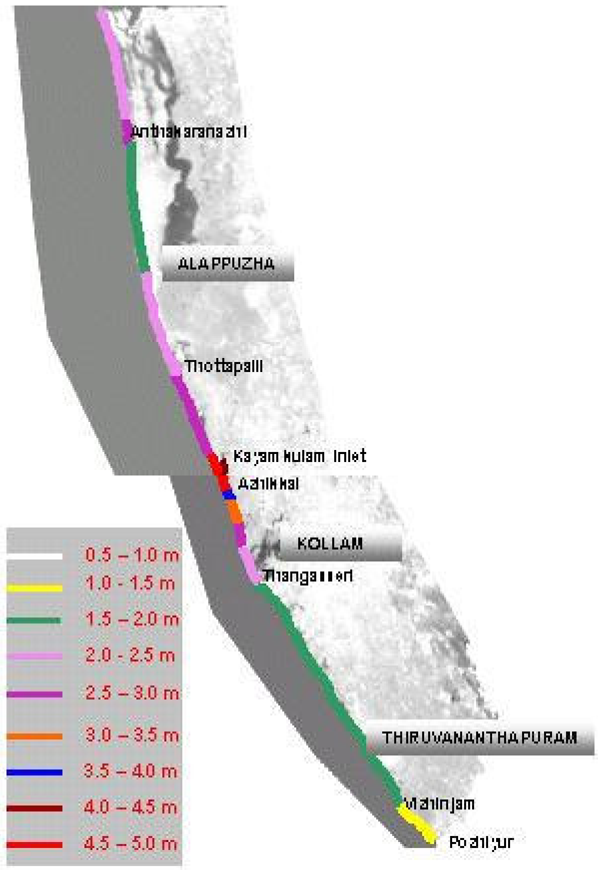


FIG 38. Run-up level map for southern Kerala coast and Alappuzha-Andhakaranazhi sector of central Kerala coast

50

location. The southern zone between Thiruvananthapuram and Alappuzha had its most disastrous effect (Fig.38). Though the run-up level and inundation was less for Trivandrum coast it picked up towards north in the Kollam coast. North of Kovilthottam, there was a drastic increase in the level reaching as high as 5.0 m at Azhikkal, just south of the Kayamkulam inlet. This was the location where the inundation and loss of life and property was maximum. In the sector immediately to the north of Kayamkulam inlet also the run-up level was up to 5.0 m. The devastation here also was quite extensive, though not as much as at Azhikkal. The run-up levels in the central zone between Alapuzha and Kozhikode varied in the range 1.0 - 3.5 m (Figs.38 & 39). However, the northern zone run-up levels varied between 0.5 and 2.5 m (Fig.40). In Balathuruth, an island in Kadalundi river, near Kozhikode tsunami waves flooded the whole island and water level rose to 2 m high.

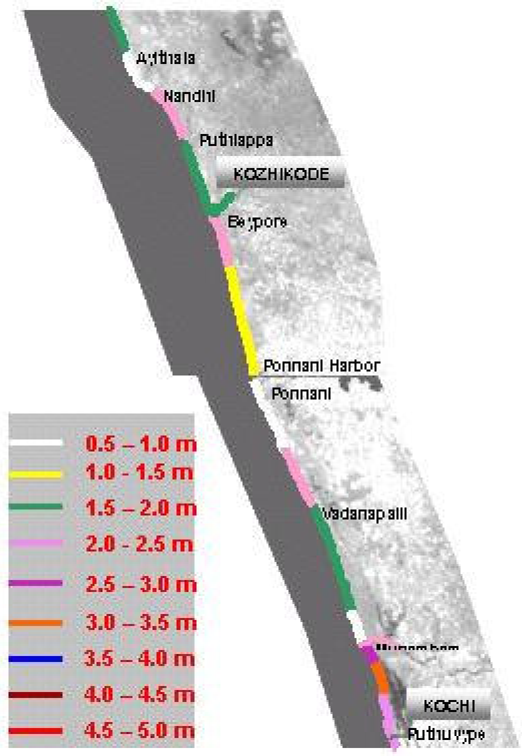


FIG 39. Run-up level map for Kochi-Beypore sector of Central Kerala coast and Kozhikode region of Northern Kerala coast

51

To sum-up, the run-up level distribution along the Kerala coast shows that it was least in the northern most sectors encompassing the Kasargod district. The sectors adjoining the Kayamkulam inlet between Kollam and Alapuzha recorded the highest level of 5 m. Significantly flooding of only up to 2 m level occurred along the Thiruvananthapuram coast, which is close to Kolachel, the location of maximum devastation along the west coast. It is summarised that the observed distribution of run-up is caused by refraction, diffraction and reflection processes. The data collected may be very useful in the calibration of the tsunami inundation model to be set up for the coast.

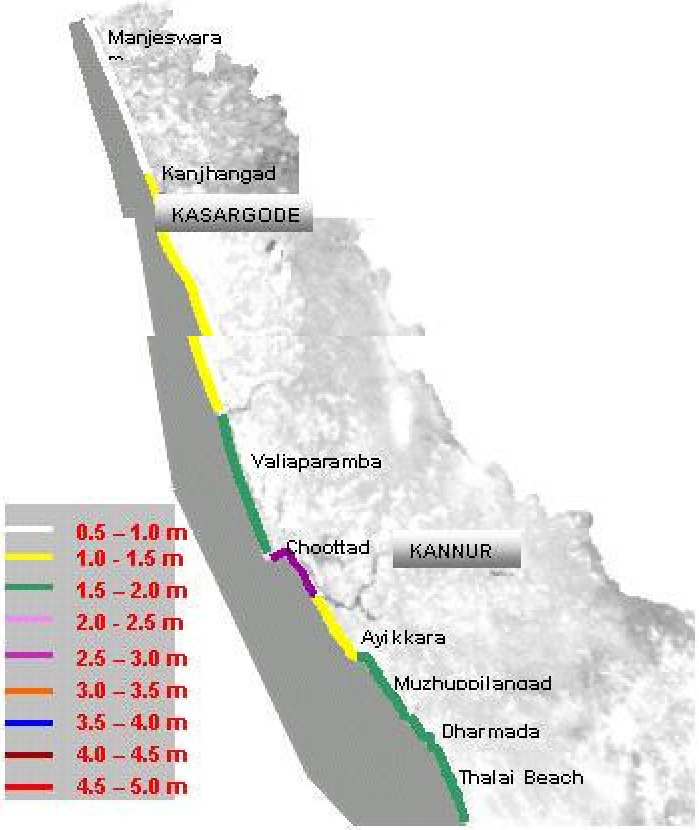


FIG 40. Run-up level map for Kannur-Kasargode sector of Northern Kerala coast.

5.5.2 Beach Profile variations and Volume Changes adjoining Kayamkulam inlet

Post-tsunami beach profiles were measured on 14th January 2005 at 9 stations where pre-tsunami beach profiles (16th November 2004) were available and where the reference stones were intact without any damage due to the tsunami. The stations for which profile changes were studied happens to be in the worst affected region surrounding the Kayamkulam inlet. This inlet has two breakwaters, north and south, jetting out into the sea for about three-fourth of a kilometer, as part of the Kayamkulam Fishing Harbour. The beach profiles are presented in Figures 41-44. The volume changes computed from the beach profiles are presented in Table 7.

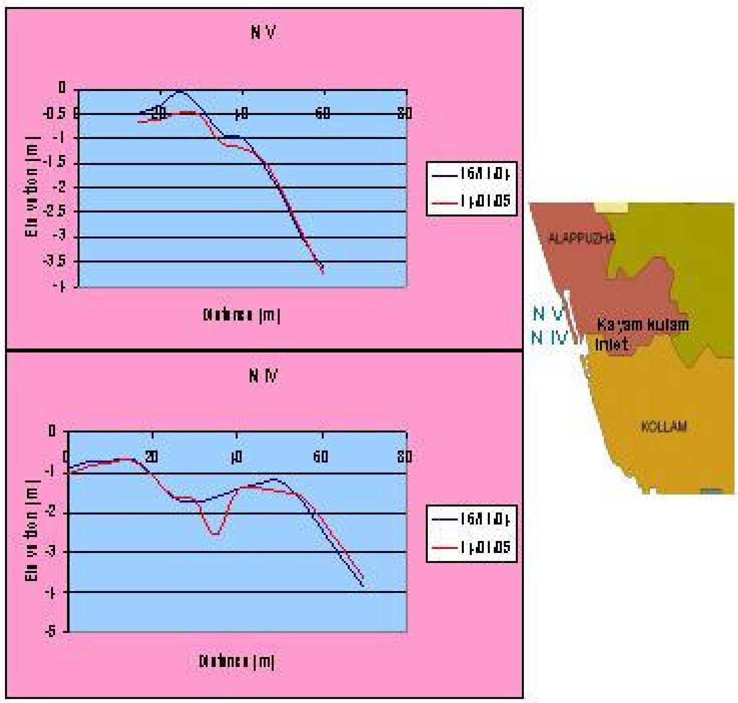


FIG 41. Beach Profiles at N V and N IV

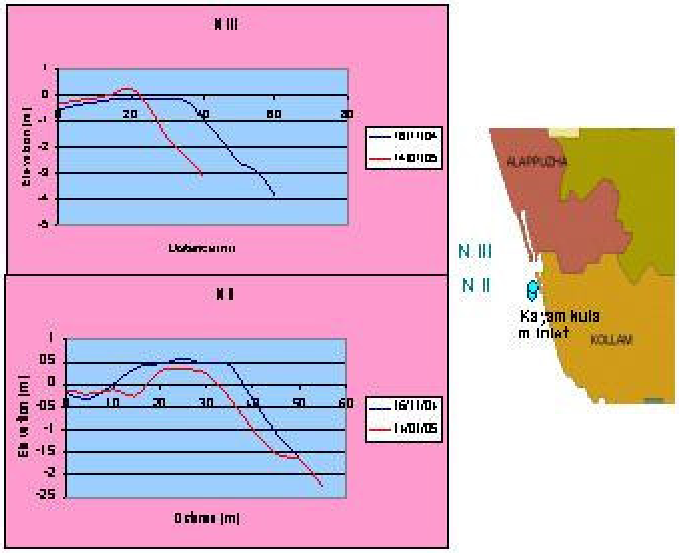


FIG 42. Beach profiles at N III and N II

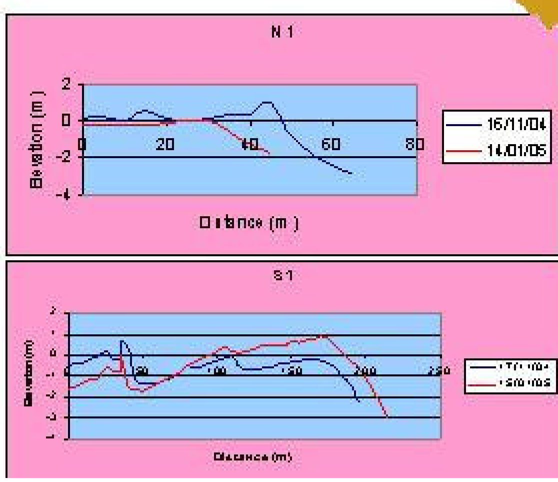


FIG 43. Beach profiles at NI and SI.

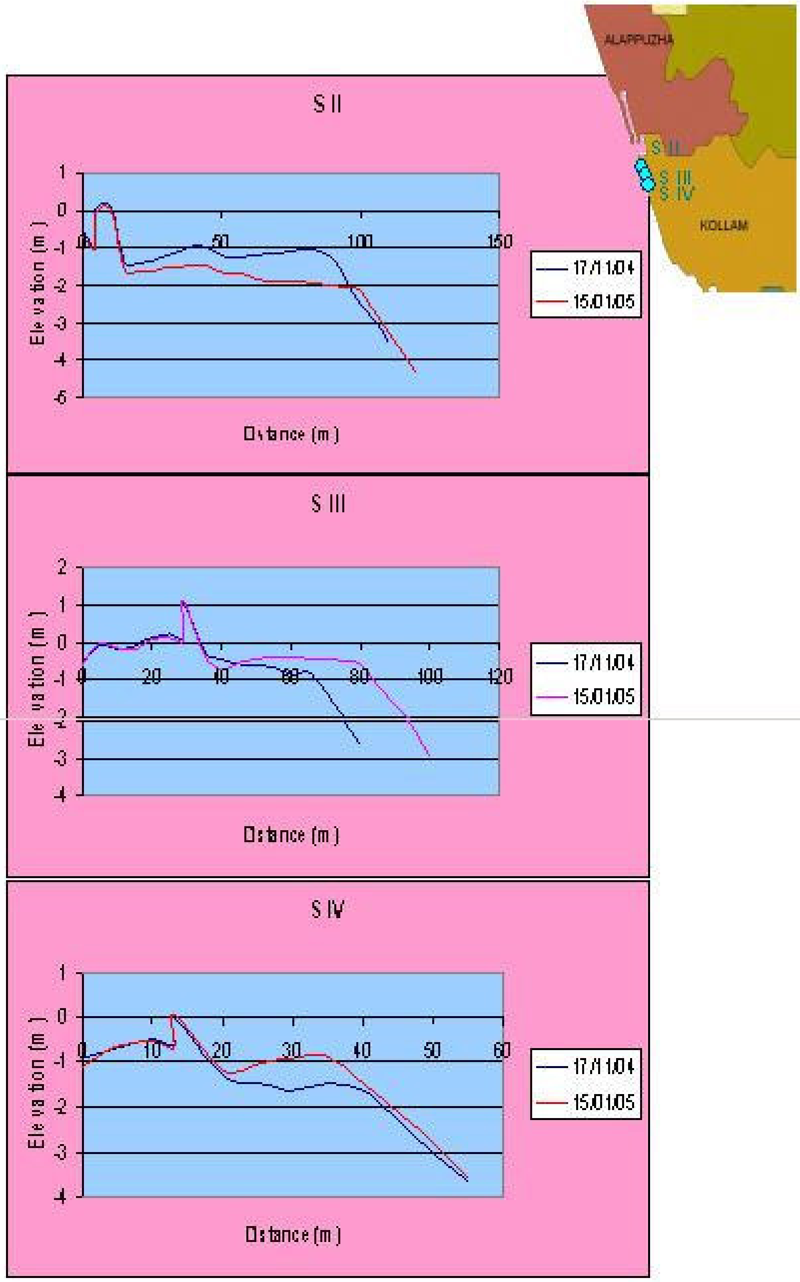


FIG 44. Beach profiles at S II, S III and S IV

TABLE 7. Volume changes at different stations adjoining the Kayamkulam inlet

S.No	Station	Status	Volume change (m^3/m width of beach)
1	N I	Erosion	53.4
2	N II	Erosion	16.1
3	N III	Erosion	66.5
4	N IV	Erosion	4.0
5	N V	Erosion	7.3
6	S I	Deposition	91.4
7	S II	Erosion	38.1
8	S III	Deposition	64.8
9	S IV	Deposition	12.6

It is seen from the Table 7 that erosion is seen in the northern side of breakwater (I1 to N V), while deposition was mostly noticed in the southern side. The erosion/deposition obtained has to be seen in the backdrop of the coastal

sedimentation processes prevalent in the area, in addition to the erosional impact of the tsunami waves. The breakwaters at the inlet, jetting out into the sea is acting as a groin, ever since the construction started a couple of years ago.

Thus huge accretion has been taking place in the southern side of the inlet due to the predominant northerly longshore currents during fair weather. Erosion has been taking place in the northern side due to the groin effect of the breakwater. In the present case the pre-tsunami beach profiles were taken on 14th November, 42 days prior to the tsunami onslaught. Thus the beach in the southern side of the inlet must have considerably accreted with respect to the pre-tsunami profile at the time of onslaught of the tsunami and thereafter till the post tsunami beach profiling on 14.1.2005. The field signatures on both the sides of the inlet showed scouring and erosion. However, the erosional effect of the tsunami was not sufficient enough to offset the depositional trend in the southernside except at station S II. In a similar way, the erosion observed in the northern side may not be entirely due to the tsunami.

Another point that has to be noted in the present case is that the erosion that took place due to the tsunami is not similar to the loss of sediment in the conventional sea-beach interaction where the sediment is lost to the sea. In the present case, the eroded sediments might have been carried further inland and got deposited in the lagoon in the hinterland side.

5.6 Analysis of Oceansat OCM Data – by NRSA, Hyderabad:

The observation of sea surface temperature data showed the fall in temperature in coastal waters of Andaman and Nicobar waters up to 1°C on the day of tsunami.

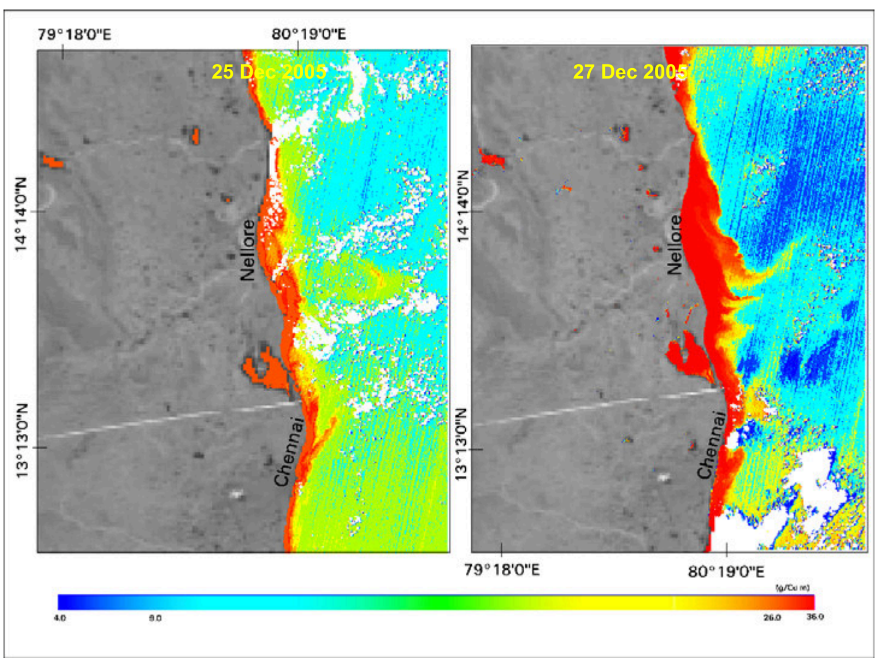


FIG 45. Distribution of Suspended sediment concentration before and after the tsunami event along Andhra Tamilnadu coast.

The tsunami had also an impact on the seawater turbidity as the successive waves churned the seabed and the reversal waves carried lot of land based wastes and soils resulting an increase in suspended particulate matter of the coastal waters as noticed from the satellite imageries between Chennai and Nellore coasts (Fig.45). The analysis of OCM data showed that suspended sediment concentrations have considerably increased along the Andhra and Tamilnadu coasts besides Andaman Islands after the tsunami event on 26 December 2004. The ranges of SSC are 9 - 21 mg/m^3 on 25 December 2004 and 4-36 mg/m^3 on 27 December 2004. Besides the increase in concentrations, the area of high SSCs had also increased from 15 km (50 m depth) to 45 km (1000 m depth) away form the north of Chennai coast. Though this is a temporary phenomenon as most of the sediment particles tend to be either dissipated towards offshore or settled to bottom, this might be having significant effect on the marine biota. Inundation of sand spit near Kakinada, closer of inlet mouth and presence of a new channel near the Pulicat Lake are some of the important observations.

The effect of tsunami is also seen on chlorophyll concentration but is gradual compared to the SSCs. Chlorophyll concentrations on 25 and 31 December 2004 are shown in Figure 46. The increase in chlorophyll concentration from 0.1 to 0.3 mg/m^3 is clear from the figure. Since the chlorophyll is increasing gradually the analysis is continuing.

Chlorophyll (mg/m3) derived from IRS-P4(OCM)

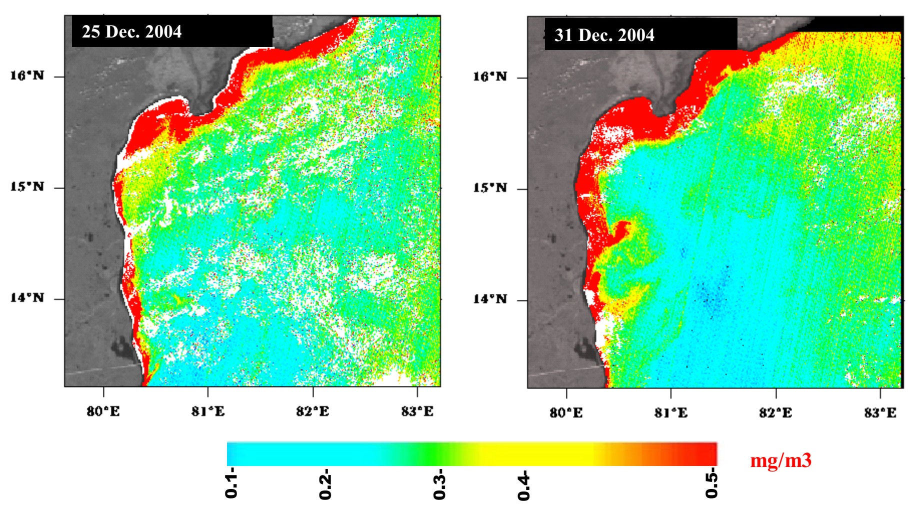


FIG 46. Spatial distribution of Chlorophyll before and after Tsunami event.

5.7 Impact of Tsunami on Biological Resources – by CAS in Marine Biology, Annamalai University, Parangipettai

The post tsunami survey made between Chennai and Nagapattinam was found to have variable results in terms of water quality, microbiology, plankton and benthos. In general the tsunami impact was found to alter the mouth region of the estuaries and backwaters. Equally the 5 and 10 km of the offshore waters also found to have more variations.

The sudden entry of tsunami waters into mouth of the rivers resulted in the release of more total nitrogen not only from the bottom derived tsunami waters but also the disturbances caused in the sediments of the mouth waters. Thus the Cooum river waters of Chennai recorded the maximum total nitrogen of 165 μM in the water column, whereas the earlier observations before tsunami was only 90.6 μM. Similarly the Nagapattinam, Cuddalore and Parangipettai waters were found to record higher levels of nutrients at 0.5 and 1 km stretch coastal waters. In general the Karaikal coastal water was found to record fairly lower level of nutrients compared to other areas. The microbial population was found to have only marginal differences between sediment and water column after tsunami. However, the sediment was found to record higher values in all the investigated areas compared to the water column. The Salmonella like organism was found to be recorded only in Nagapattinam and Chennai coastal stretches up to 10 km in the water, a unique feature after tsunami. Most of the forms were recorded more in the 0.5 and 1 km stretch was now recorded in the 5 and 10 km stretches (Table 3). This could be the post tsunami case for most of the coastal areas.

The blooming of phytoplankton *Lauderia borealis* (1,05,000-3,22,993 nos/l) was recorded only in coastal waters of in and around Chennai (Ennore, Cooum, Chennai harbour, Muttukadu). However, it is not recorded in other areas.

The occurrence of zooplankton pollution indicator species like *Cresis sp.*, Lucifer and *Oikopleura sp.*, is felt in parts of Tamilnadu and Pondicherry after tsunami (Fig.47). The distribution of zooplankton *Cresis sp.* was restricted to Cuddalore and Ennore coasts. The Lucifer having restricted distribution before tsunami is seen significantly all along Tamilnadu and Pondicherry coast after tsunami. The zooplankton

Oikopleura sp was found to record higher (35,000/95,000 nos/m^3) in the Tamilnadu and Pondicherry coastal waters, instead of restricted distribution in harbour waters.

FIG 47. Pollution indicator Zooplankton species found in coastal waters of Tamilnadu and Pondicherry after tsunami

In general very low numbers of benthic fauna (1-9/0.08 m^2) and species (15) were recorded from Chennai to Nagapattinam coastal as well as the hot spot areas after tsunami survey. However, higher number (~146/0.08 m^2) and diversity (35 species) were recorded at Cooum 0.5 km. Besides, the polychaete *Polyodontes melanonotes* (~2500/0.08 m^2) was found to record only in Pondicherry hot spot area for first time (Fig.48).

FIG 48. *Polyodontes melanonotes* found in Pondicherry hot spot area.

The net impact of tsunami is that significant amount of nutrients were added to the coastal waters from terrestrial sources, mixing up of nutrient rich bottom waters, as well as from sediments which seems to trigger the biological production and leads to the promotion of chlorophyll levels. Added to this, the sewage mixed in coastal waters extended to distances even up to 10 km from shore which has promoted sewage feeding microbial organisms like *E.coli, Faecal* coliforms, Salmonella, etc. to these far off places when they were seen up to 3 km from coast before tsunami.

5.8 Ecological impact of Tsunami on the southwestern coast of Kerala and Tamilnadu - by RRL, Trivandrum

The coastal belt from Thottapally in Kerala to Kanyakumari in Tamil Nadu was monitored during January 2005. Transects were selected based on the basis of the

intense impact of Tsunami. At each transect, stations were chosen at 5 km intervals, up to a distance of 25 km from shoreline. Water quality data after tsunami showed a slight deterioration at some of these transects (Table 8).

TABLE 8. Comparison of water quality of selected coastal transects before and after Tsunami

Parameter	Kayamkulam		Aleppey		Vizhinjam	
	Before	After	Before	After	Before	After
Temp (°C)	28.26	28.26	28.53	28.50	28.26	28.26
Salinity	33.24	33.62	33.54	33.75	33.24	33.82
pH	8.30	8.21	8.32	8.16	8.30	8.16
DO (mg/l)	5.67	4.84	5.61	5.85	3.16	4.69
NO_2 (μM)	1.69	0.18	0.13	0.38	0.04	1.69
NO_3 (μM)	3.22	3.25	--	3.88	1.29	4.25
SiO_4 (μM)	4.01	2.34	1.90	2.72	1.30	2.52
PO_4 (μM)	0.30	1.58	0.60	1.96	0.19	1.86

The post-tsunami results indicated that the marine environment in the southwest coast between Thottapally and Muttam has been affected as a result of the impact of tsunami. This is reflected by the following assessments:

* The concentrations of nutrients have decreased.
* Primary productivity has been drastically reduced.
* The species diversity of plankton is lowered.
* The fish catch is affected.
* The microbial population has decreased.
* The sediment samples collected offshore, have more of coarse sands, indicating their transportation from the coast.
* The presence of heavy minerals in the sediment samples collected as far as 25 km offshore indicate that along with coarse sands these have also been transported due to high-energy backwash.
* The impact of Tsunami was maximum at Vizhinjam due to the geomorphic feature resembling inland basin.

5.9 Coral reef ecosystems of Gulf of Mannar and Palk Bay - by Madurai Kamaraj University

Diving personnel of the Coral Reef Research and Monitoring group attached to the Center for Marine and Coastal Studies of Madurai Kamaraj University, made a rapid survey on the post-tsunami impact in selected islands of Gulf of Mannar and reef areas of Palk Bay on the northern side of Rameswaram and Mandapam.

The underwater surveys using Line Intercept Transect Method (LIT) revealed that there were no appreciable changes in the Bio-physical status of corals in the Gulf of Mannar. Coral species of the family Acroporidae which are vulnerable to the natural disturbances did not show any damage in their structures after the tsunami waves in the Gulf of Mannar. Also the massive corals and associated fishes, algae and sea grass beds were not affected by the tsunami waves. There was the slight displacement of the coral rubble walls lying near the edges on the seaward side of some of the islands of the Gulf of Mannar.

However, the survey of the corals of the Palk Bay region showed an increase in sedimentation near the coral reef areas after the incidence of tsunami waves. This is based on sediment traps already placed in several locations of the Palk Bay coral habitats for an ongoing research work. The sedimentation rate recorded earlier as 32.5 mg/d in November 2004 had increased to 53.4 mg/d after the incidence of tsunami tidal wave flushing in the Palk Bay region. Some corals exhibited partial bleaching near Pamban viaduct. Reports of people and fishermen in the region confirmed that the water level raised up to 1 meter and then receded back to normal. There was no significant flooding in the nearby coastal areas.

As described earlier, the island nation of Sri Lanka has blocked and deflected the approaching tsunami waves and hence the coastal areas of the districts of Pudukottai, Ramanathapuram, Tuticorin and Tirunelveli were saved. Because of the deflection of the waves, the water had receded temporarily in some places before returning to normal. For instance the rocky bed which used to be always under water in Tiruchendur coast (near Tiruchendur temple) got exposed because of the receding water up to 50 meters from the normal low tide mark. Indications are that sediment load might have increased due to the sudden flushing effect of the tsunami waves and hence there is a need to make a complete survey of all the coral reef habitats

around the chain of 21 islands in the Gulf of Mannar. The preliminary survey concluded that the impact of tsunami waves on either the corals or on the ecosystem was only minimal.

6 Inferences

The tsunami is an eye opener on set back lines decided for protection/conservation of coastal resources, beaches, protection of land, people, etc. Generally setback lines are decided in terms of distance from High Tide Line as done under the CRZ Notification. The run-up levels due to increase of sea level during tsunamis as well as during storm surges have added another dimension of elevation to be taken into consideration in the principle of setback line based coastal zone management. It is necessary to incorporate the elevation levels for new/expanded settlement areas under the Town and Country Planning Acts so that the human and property are saved from the natural hazards/vulnerabilities. The low lying areas like Nagapattinam, Nellore to Machilipatnam, Paradip to Bangladesh border, Kachchh coast in Gujarat, Andaman & Nicobar islands, etc. need immediate attention in this regard. Maps demarcating the extent of land areas vulnerable to seawater inundation and safe locations for settlement, schools and vital infrastructure need to be prepared for all areas in the country. Where possible, the settlements and other human gathering locations like schools, theme parks, etc. need to be located at safer locations in a phased manner.

The fact of less damage to coastal villages located in elevated areas with wide beach front like Kalanji in north Chennai, mangroves shielding Killai village in Pichavaram mangrove have laid great importance for the need to protect beaches, mangroves, coral reefs, offshore shoals, etc. as they act as excellent natural barriers. It is necessary all developmental activities both existing and planned in the future need to adopt the construction codes stipulated for their region (for example, seismic codes for high risk zones like Andaman and Nicobar islands, Kachchh areas) and adopt best environmental practices to minimise loss or damage of natural barriers and to ensure protection of human life. The huge loss of human life (about 8000) in villages located close to the coast (like Keechankuppam, Akkaraipettai, Devanampattinam in Tamilnadu) amply demonstrate the vulnerability of human

settlement located/occupied close to the coast, despite these areas had a beach front of 100-200 m.

Acknowledgements

Our sincere thanks to Dr.Harsh K.Gupta, Secretary, Department of Ocean Development for his keen support in preparing this report. Thanks are also due to Dr.V.Krishnamurthy, Director, Fisheries and Science & Technology, Andaman and Nicobar Islands and other A&N Administration Departments for their logistic support while carrying out the survey. The technical staff of ANCOST, NIOT helped to a great extent in data collection.

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